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PRELIMINARY ENVIRONMENTAL ASSESSMENT OF SOLAR ENERGY SYSTEMS

Interagency
Energy-Environment
Research and Development
Program Report

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DISCLAIMER

FOREWORD

When energy and material resources are extracted, processed, converted, and used, the related pollutional impact on our environment and even on our health often require that new and increasingly more efficient pollution control methods be used. The Industrial Environmental Research Laboratory Cincinnati (IERL-Ci) assists in developing and demonstrating new and improved methodologies that will meet these needs both efficiently and economically.

This report addresses the environmental consequences of three kinds of solar energy utilization: photovoltaic, concentrator (steam electric) and flat plate. The application of solar energy toward central power generating stations is emphasized. Discussions of combined modes and of the geosynchronous satellite generating stations are included. Numerous conclusions and recommendations are developed. These should be useful to U.S. Environmental Protection Agency (EPA) personnel concerned with environmental quality related to power technology and conservation, to EPA and other Federal agency personnel concerned with manufacturing processes in support of solar energy development, and to Federal personnel assessing long-range goals and tradeoffs consequent to other advanced energy developments.

For further information on these subjects, interested readers should contact the Power Technology and Conservation Branch of the Energy Systems Environmental Control Division.

David G. Stephan
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ABSTRACT

Central station solar-electric plants and flat plate space heating installations are environmentally superior to their respective conventional alternatives because they produce little or no air and water pollution. Both kinds of installations will require storage systems, also relatively clean environmentally.

Land area required for central station solar plants will be large, but it is not as destructive or irreversible as with coal stripping. The ecological impact of solar plants can be serious as a result of vegetation destruction. Visual effects can be extensive, with no mitigating technology. Weather modifications may occur. Geosynchronous satellite generating stations could be environmentally catastrophic from pollution caused by large numbers of Space Shuttle launchers.

Some photovoltaic materials, such as gallium and cadmium may be resource limited. Indirect effects, resulting from the production of large quantities of photovoltaic materials, could be environmentally harmful.

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ACKNOWLEDGMENTS

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SECTION I
INTRODUCTION

SCOPE AND OBJECTIVES

This report is devoted to three solar energy utilization technologies: photovoltaic, flat plate, and concentrator. Areas of application included are residential, commercial, industrial and utility. Space and maritime applications are excluded.

Lockheed-Huntsville has prepared this report to assist the U.S. Environmental Protection Agency (EPA) in: (1) identifying potential beneficial and adverse environmental consequences of a major solar energy development; (2) phasing its R&D efforts so that timely and appropriate technical solutions and regulatory postures may be developed in anticipation of major solar power development, to help reduce reliance on ad hoc responses; and (3) identifying the directions of current research efforts funded by other agencies, areas needing additional EPA R&D effort and funding, and the developments likely to require earliest concentration of effort in pollution abatement technology.

The third point, above, has been accomplished in part by compiling a comprehensive list of Federally sponsored, solar-related research, which will be submitted later as an appendix to this report. However, this report stands by itself. A similar compilation of privately funded solar projects might be useful to EPA but is not part of this task.

THE NATIONAL PLAN

As part of a broadly based effort to develop our domestic energy resources, various Federal agencies and their contractors have a mandate to explore, develop, demonstrate, and encourage market penetration of a variety of advanced energy sources. The lead agency is the Energy Research and Development Administration (ERDA).

An overall strategy has been articulated by ERDA in two basic reports constituting "A National Plan for Energy Research, Development and Demonstration," ERDA 48, Vols. 1 and 2 (Refs. 1 and 2). These reports constitute the basic documents on the entire program, setting forth goals, strategy, and implementation plans. Further elaboration of the Federal programs specific to solar heating and cooling is found in ERDA-23A (Ref. 3). Other approaches to solar energy utilization are presented in ERDA-49 (Ref. 4). These four reports to the President and Congress were examined by the Congressional Office of Technology Assessment (OTA), which issued its analysis and critique in a fifth volume (Ref. 5). The latter volume includes some criticisms especially relevant to the concerns of EPA. In particular, environmental tradeoffs and societal and institutional aspects of environmental acceptability are discussed.

One must assume that these five documents fairly represent current best guesses concerning goals, rates of development progress, demonstration, and market penetration for solar energy utilization as well as utilization of other energy forms. To the degree that this assumption is correct, they can be used by EPA to administer the phasing of its energy related research and development.

SOCIO-ECONOMIC AND POLITICAL CONSIDERATIONS

Socio-economic analyses related to solar energy development and marketing are extremely important and may indeed have significant impact on environmental decision making. Examples are Federal tax incentives for energy conservation in homes, small business administration encouragement of solar-architectural enterprises, FHA appraisal rules relative to conservation (e.g., storm windows), and local tax structures relative to residence-sited solar heating and cooling installation. All these factors influence the decisions of residential property owners and business investors. A variety of other institutional, political, community motivation, economic, and other non-technical matters more or less directly affect costs and incentives, and thus market penetration.

It is recommended that these socio-economic and motivational factors be studied by professionals in those fields and in community and regional planning. We believe at least some of these studies should be conducted by contractors to EPA and not in-house. These matters are excluded from this report unless related very directly in a definable way to environmental problems.

INTERNATIONAL ASPECTS

Matters relating to international relations are important and may have environmental significance. For example, increased use of coal and uranium instead of foreign oil, relations between foreign and domestic mineral resources, possibilities of international collaboration in solar development, and opportunities to export solar technology and high technology products — all relate to goals-priorities, participation of non-Federal funds, etc. Of these, only the matter of foreign and domestic mineral resources is discussed in this report, for some solar developments will severely strain or exceed domestic resources.

Sunlight is not a "strategic material." Solar energy development seems to have only a second-order effect on a nation's defense capabilities. Thus a prime opportunity exists for truly international collaboration in solar energy research. Likewise, most advanced nations are likely to have some concern for the environmental consequences of advanced energy developments. Unfortunately, little international collaboration occurs today (Ref. 6).

PREVIOUS ASSESSMENTS

An enormous volume of recent literature exists in the area of solar energy systems design, economics and utilization projections. Almost none of the literature deals in any direct and substantative way with environmental matters. There have been a few published environmental studies, however, and more are currently in progress.

Dickson (Ref. 7) at the Stanford Research Institute and Griffith (Ref. 8) at the EPA Industrial Environmental Research Laboratory, Research Triangle Park, N. C., have both performed EPA-funded preliminary surveys.

The Atomic Energy Commission (now ERDA) included a cursory study in the Environmental Statement for the Liquid Metal Fast Breeder Reactor (Ref. 9).

Very recently MITRE Corporation (Ref. 10) completed three studies sponsored by ERDA's Division of Solar Energy: a pilot solar thermal central receiving station (not site specific); the Solar Thermal Test Facility at Sandia; and a Solar Total Energy system at Ft. Hood, Texas. The project officer at ERDA was J. W. Benson.

Lawrence Berkeley Laboratory (Ref. 11) has underway a $100K program to study environmental aspects of solar and geothermal energy. Approximately 40% of the effort is to be solar. This is funded by ERDA.

Stanford Research Institute reportedly (Ref. 12) has a $195K ERDA-funded program to examine long-term socio-economic effects of nine advanced energy technologies, including solar.

At EPA's Las Vegas research center, Donald Gilmore's (Ref. 13) office is contemplating an environmental assessment project, to include photovoltaic, flat plate, and power tower methods. Funding has not yet been "identified."

In the private sector, the Electric Power Research Institute (Refs. 14 and 15), Palo Alto, Calif., has just comissioned two projects: Black & Veatch, Kansas City, Mo., are under a 20-month, $323K contract to study five solar energy technologies, including solar-thermal and photovoltaic. Also Woodward-Clyde, Consultants, San Francisco, have undertaken a 19-month, $293K project to study solar-thermal conversion and wind power using what is described as an advanced assessment methodology to be developed by them.

Of these studies, only the original Dickson (SRI) study and the AEC-LMFBR statement are readily available in the public domain. The others are either internal agency documents, have yet to be initiated, completed or issued, or are private and proprietary. As major solar projects progress well into the planning stage, we can expect to see increasing numbers of NEPA-mandated environmental impact statements published. The preliminary studies such as this report may suggest areas requiring detailed attention in subsequent environmental impact statements.

SECTION II

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

1. Central station solar electric plants and flat plate space heating installations are environmentally superior to their respective conventional alternatives because they produce little or no air pollution or water pollution (aside from the cooling tower effects in solar steam/electric applications).
2. Little is known about the environmental impact of large-scale manufacturing of photovoltaic materials and cells.
3. Three photovoltaic materials seem to show greatest near term promise: Si, CdS and GaAs. Si will be used for the first pilot and demonstration plants, probably with optical concentration. It is quite unclear what photovoltaic materials and manufacturing processes will prevail in the long term.
4. Solar generating stations will require storage in order to conform to current utility industry operating philosophies. Pumped hydro and batteries will see nearest term use. Favored battery concepts now are Li-S and Na-S, but those are not sufficiently well developed for immediate utility application. Consequently, large conventional Pb-acid batteries may see near term use, together with pumped hydro if siting permits.
5. Hydrogen cycle and flywheel storage systems are being developed and ordered for small peaking applications. They may prove satisfactory for large storage someday. They are clean environmentally.
6. Solar photovoltaic (but not solar steam/electric) generation is particularly suitable for grid dispersed application. Significant energy economies result from placing generating capacity near load centers. This also may reduce currently perceived incentives for very high voltage transmission lines.
7. Photovoltaic plants require no cooling water, no steam water, and no process water, and therefore, cause no degradation of surface water quality due to chemical additions or thermal plumes. This also makes them especially suitable for water-short regions of the arid Southwest
8. Land surface alterations over very large areas (for either photovoltaic or steam/electric) could lead to perturbations in subsurface hydrology.

9. Estimates of land area required for central station solar plants range from 4.5 to 30mi^2/1000 MW. This land commitment is not as destructive and not as irreversible as a commitment for coal stripping. The 30-year cumulative land area required for coal stripping to support an equivalent capacity fossil plant ranges from 30% less to 500% more than that needed for solar plants.

10. Land prices will not soon be a determining factor in utility market penetration by the solar industry, because currently photovoltaic materials and optical and sun-tracking components are overwhelmingly more important cost elements, and vast areas of low productivity Federal lands are available in the U.S. Southwest.

11. Ecological impact of solar plants can be profound. The key element in this impact is the alteration or destruction of vegetation directly by construction or indirectly by shading.

12. Visual effects of solar plants can be extensive. Mitigating technology does not exist.

13. Large-scale solar station developments could have some micro-climate/weather modification impact through:

    - Avoidance of particulate and CO_2 emissions from fossil fuel combustion
    - Avoidance of cooling towers (photovoltaic only)
    - Possible local effects on earth's albedo
    - Reduced boundary layer velocities.

14. Photovoltaic installations (and to a lesser extent steam/electric) seem to be less vulnerable to sabotage, terrorism, major fires, and seismic events than are coal fired and nuclear installations.

15. Proposed siting of central station photovoltaic plants on geo-synchronous satellites has some potential to become environmentally catastrophic. Principal problems are:

    - Very large number of launches annually with unconfined combustion of huge quantities of propellant fuel. This fuel will probably be $NH_4C\ell O_4$ plus $A\ell$ plus organic nitrogen compounds.
    - Beaming of power back to earth using microwaves
    - Local noise effects, which could be avoided by resiting the launch centers
    - Possible use of nuclear-powered space tugs. In the event of a Space Shuttle launch abort followed by disintegration and burnup, nuclear materials could be released to the atmosphere.

    A major environmental benefit of the geosynchronous satellite station is the greatly reduced construction materials requirement.

16. Silicon photovoltaic plants are not resource limited, but CdS and GaAs probably are. CdS or GaAs needed for a single 1000 MW photovoltaic represents a few percent of known U.S. domestic reserves of Cd or Ga.

17. Glass, steel, aluminum, silicon, and lead energy costs are signifi cant cost elements but not prohibitive.

18. The air and water pollution and soil contamination aspects of metal smelting and refining have been studied intensively and continue to receive regulatory attention. Shifts in product mix caused by major solar demands for Ga, In, etc., may require new technology.

19. Environmental health and toxicity and perhaps some industrial hygiene aspects of Ga, In and Sb are not well known. Practically nothing has been reported on effects on aquatic biota.

20. Steam/electric concentrator systems share many advantages of photovoltaic generation but differ as follows:

    - Cooling towers and/or ponds are required.
    - Being non-modular, grid dispersal is unlikely.
    - Visual impact is greater.
    - Weather modification effects may be more significant.
    - No silicon, CdS, or GaAs are required.

21. Steam/electric installations are likely to become economically justifiable much earlier than photovoltaic.

22. Liquid metals (e.g., Na) have been suggested for heat transfer fluid and possibly thermal storage. Environmental consequences of an accident involving large quantities of sodium are unknown.

23. Solar heating and heating/cooling technology is well understood. Widespread application awaits major improvements in reliability and cost pictures. Heat driven air-conditioning seems very unpromising financially when not integrated into a heating/cooling system.

24. Corrosion problems cause limited lifetime and acceptance of liquid-in-aluminum or steel collectors. Capital costs have limited liquid-in-copper.

25. Flat plate collection is not suitable for most industrial process heat applications. It may find application to food and feed processing and certain industrial applications needing low-grade heat.

26. Thermal storage in flat plate applications is absolutely essential. Currently, water tank heat storage is used for liquid-in-metal collectors, and rocks are used for air-in-metal systems. Phase change materials (PCMs) and chemical change materials (CCMs) are technically attractive but financially prohibitive in residential application.

27. Flat plate collectors probably cannot receive widespread use inside large cities; suburban residential applications are more likely. Land use commitment and air pollution potential are negligible or zero. Glare can be offensive. Flat plate collectors may reduce the currently observed heat inbalance and heat bubble effects over major metropolitan areas.

28. Groundwater and soil contamination by corrosion inhibitors (especially chromates), algaecides, and non-aqueous heat transfer fluids is possible and could become severe if projected uses are correct (3×10^6 lb corrosion inhibitors and 4×10^6 lb heat transfer fluids by year 2000).

29. A major environmental advantage of all solar technologies is avoidance of coal mining and fossil fuel combustion. Further, solar generating stations in the Southwest could relieve large energy shortfalls caused by exhaustion of natural gas supplies. Flat plate collection alone is projected to save 830×10^6 gal of oil in year 2000.

RECOMMENDATIONS

1. In collaboration with other Federal agencies, EPA should encourage application of solar technologies.

2. EPA should perform studies of social, economic, and community factors which will influence selections among various energy options, especially solar, and of the socio-economic impact of major advanced energy developments.

3. EPA should perform environmental assessments of very large scale manufacturing of following photovoltaic materials and cells: Si, CdS, and GaAs. Similar assessments on other candidate materials should be commenced as soon as it appears that they are likely to become important.

4. Emphasis should be placed on effects of the new "exotics" on aquatic biota. This refers especially to Ga, and secondarily Sb and In.

5. EPA should perform environmental assessments of new energy storage technologies — both central station and residential.

6. EPA should perform initial studies of possible microclimate/weather modification effects of:

   - Cooling towers in arid Southwest
   - Boundary layer velocity changes
   - Heat balance effects.

7. EPA should immediately begin a thorough review and assessment of the environmental (especially air pollution) effects of Space Shuttle launches supporting construction of satellite-sited photovoltaic generating stations.

8. EPA, ERDA, Interior, and DOD should review resource limitations of photovoltaic and storage materials, especially Cd, Ga, Li, Pb, Cr.

9. EPA and ERDA should review the recycle possibilities for these same materials as well as As and In.
10. EPA should develop fine particle control technology for metal fumes, especially Cd, Ga, GaAs, and also CdS.
11. EPA should perform intensive studies (independent of the utility industry) of effects of air pollution on vegetation in the arid Southwest and high arid northern plateaus.
12. EPA should examine the environmental impact of the transportation demands of large-scale central solar plant construction in the Southwest.
13. EPA should examine the consequences of major accidents involving molten metal heat transfer media.
14. EPA should produce an approved list of residential and commercial storage materials (including PCMs and CCMs) and aqueous corrosion inhibitors.

SECTION III

ENERGY PROJECTIONS AND GOALS

Reports ERDA 23A, 48 and 49 contain extensive ERDA estimates and flow diagrams of energy production modes and consumption, and tabulations of resource consumption, and pollutant release. These parameters are presented as functions of several "scenarios" in Figures 1 and 2 and in Tables 1 and 2. The background and descriptive information for these scenarios are presented in Appendix A, projected to the year 2000. In none of these scenarios is solar electric energy production conceived to reach 2% of coal electric.

Figures 1 and 2 present overviews of the consequences of the various scenarios. Particularly striking is the rapid approach to uranium exhaustion in scenarios O, II and III even though III includes breeder reactor participation. Scenario I is most effective from nearly all points of view, and its success is primarily due to improved efficiencies in end use, with only token contributions from advanced energy sources. These scenario presentations serve to illuminate our very restricted options. They suggest that an aggressive conservation campaign should accompany any advanced energy development program.

Tables 1 and 2 present quantitative resource commitment data, and direct and indirect environmental residuals for 1985 and 2000. These tables reemphasize that conservation is the most benign scenario, from the environmentalist's point of view.

ERDA fails to specify the emission factors and other parameters used to calculate the pollutant data. Further, the tables contain no entries for heavy metals and other "exotic" pollutants which are potential problems of some advanced energy systems. A goal of this report is to call attention to potential problems with "exotic" residuals arising from solar energy exploitation, particularly photovoltaic.

Finally, Tables 3 and 4 display the goals and priorities ERDA had established as of June 1975. Even though solar electric can make only a small contribution by the year 2000, our options are so restricted then and later that ERDA has ranked solar electric among its highest priorities. ERDA 76-1 is now scheduled for release in March 1976. It is possible that newly revised estimates will appear in that document.

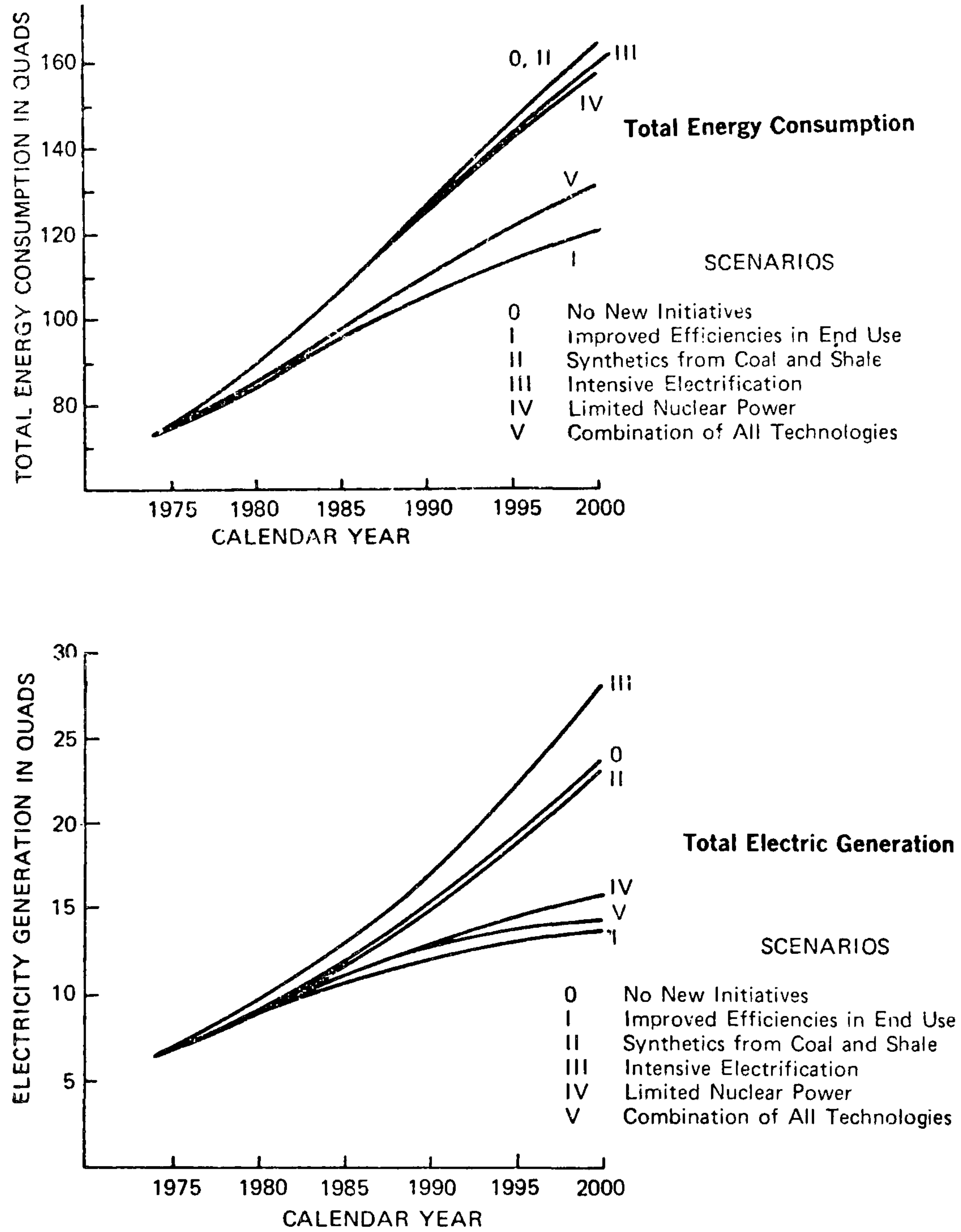
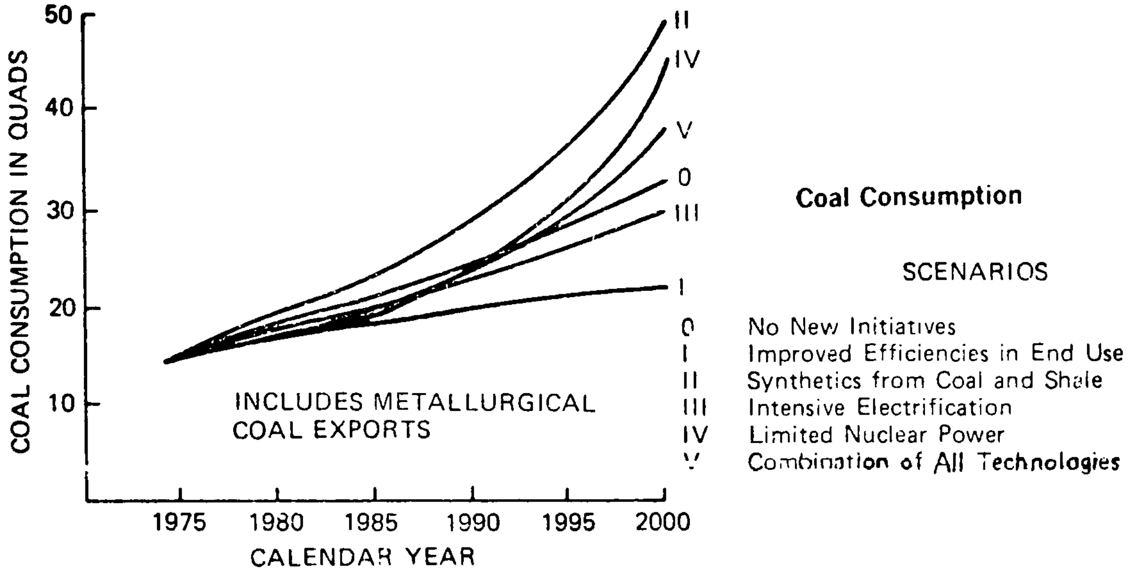


Figure 1. Comparison of electric generation with total domestic energy consumption (Ref. 1).



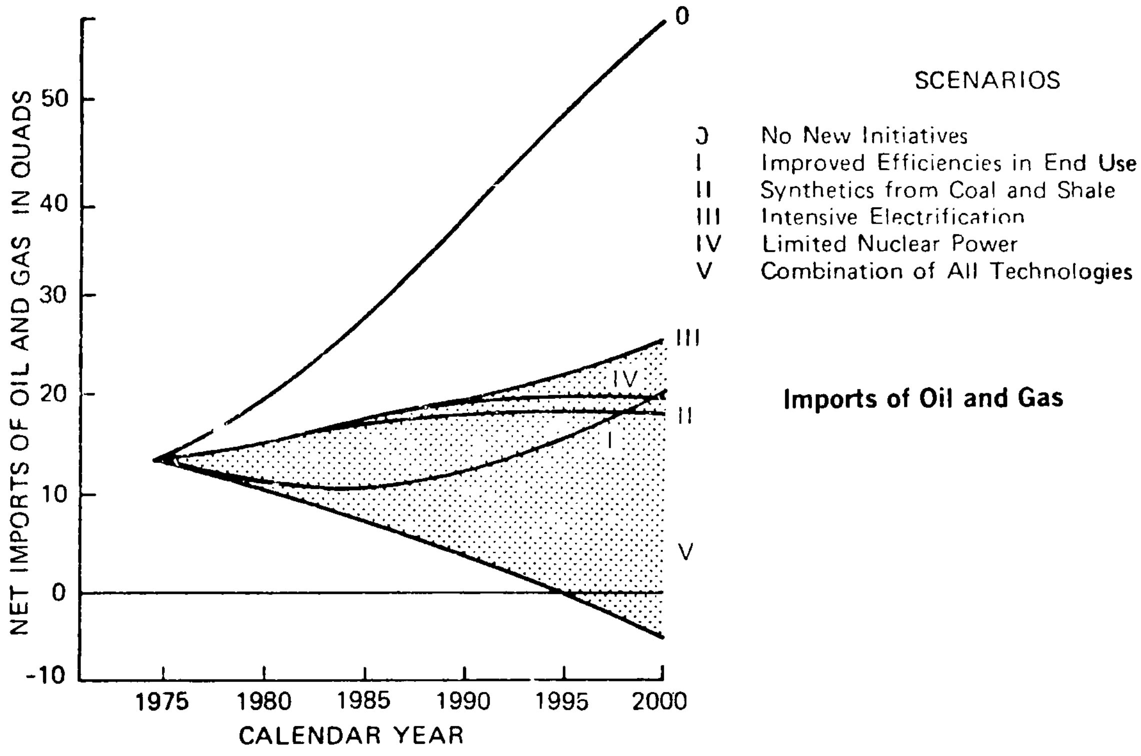


Figure 2. Conventional fuels consumption (Ref. 1).

(Continued)

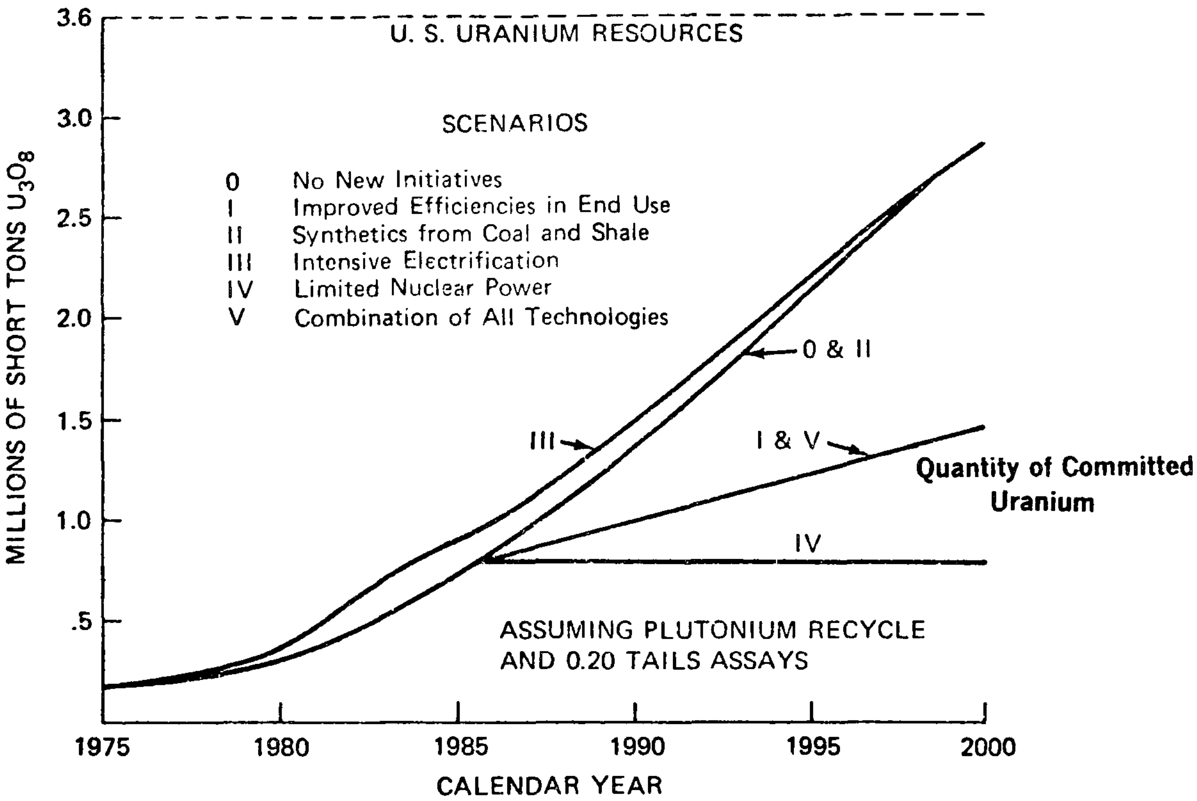


Figure 2. Conventional fuels consumption (Ref. 1).

(Concluded)

TABLE 1. 1985 SCENARIO RESULTS (REF. 1)

	Resources Consumed, Quads (10^{15} Btu)					
	0	I	II	III	IV	V
	Year 1985 Scenario Results—Resources					
Hydroelectric (at 34% efficiency)	3.38	3.38	3.38	3.38	3.38	3.38
Geothermal	0.69	0.93	0.69	1.60	3.20	1.50
Solar	0.00	0.25	0.00	0.31	0.57	0.31
Fusion	0.00	0.00	0.00	0.00	0.00	0.00
Light Water Reactor (LWR)	10.61	10.61	10.61	12.97	10.60	12.97
Liquid Metal Fast Breeder (LMFBR)	0.00	0.00	0.00	0.00	0.00	0.00
High Temperature Gas Reactor (HTGR)	0.24	0.25	0.24	0.24	0.25	0.25
Oil Steam Electric	3.39	2.79	3.39	4.91	2.32	2.79
Gas Steam Electric	4.39	3.00	4.39	3.19	4.03	3.00
Oil, Domestic and Imports	47.14	34.59	41.43	41.57	41.52	31.95
Oil Imports	25.94	10.49	17.33	17.47	17.42	7.85
Oil Shale	0.00	0.00	1.00	0.00	1.00	1.00
Natural Gas, Domestic and Imports	24.00	26.50	26.50	26.50	26.50	26.50
Coal (including 1.5 Quads exports)	21.14	18.46	23.28	20.10	19.98	18.13
Coal (million tons per year)	1006	879	1108	957	951	863
Waste Materials	0.10	2.00	0.10	0.10	0.00	2.00
Biomass	0.00	0.00	0.05	0.00	0.05	0.05
Total Energy Resources (including exports)	107.30	96.97	107.28	106.77	107.05	98.14
Total Cost in Billions of Dollars per year	226.63	198.17	224.94	223.74	218.57	197.15
Average Cost in Dollars per Million Btu of Resources Used	2.11	2.05	2.10	2.10	2.05	2.01

	Year 1985 Scenario Results—Environmental Effects					
Centralized Air Pollutants						
Carbon Dioxide (CO_2) 10^{11} pounds	40.5	36.2	40.5	41.5	35.7	30.6
Carbon Monoxide (CO) 10^{9} pounds	55.1	52.0	55.1	55.6	50.5	42.0
Nitrogen Oxides (NO_x) 10^{9} pounds	12.2	11.1	12.2	12.5	10.8	9.3
Sulfur Dioxide (SO_2) 10^{9} pounds	18.7	17.4	18.7	19.8	16.5	14.3
Particulates 10^{8} pounds	68.5	64.7	68.5	69.2	62.3	52.2
Hydrocarbons (HC) 10^{8} pounds	3.6	2.9	3.6	3.4	3.2	2.6
Decentralized Air Pollutants						
CO_2 10^{11} pounds	97.5	80.7	95.7	86.7	91.4	80.6
CO 10^{9} pounds	6339.6	5818.9	6223.1	6129.5	6321.2	5573.7
NO_x 10^{9} pounds	24.8	21.5	24.2	22.6	23.6	21.5
SO_2 10^{9} pounds	16.0	9.6	13.2	11.3	12.5	9.7
Particulates 10^{8} pounds	160.7	134.2	157.1	137.3	119.5	133.9
HC 10^{8} pounds	133.8	119.8	132.2	129.8	133.3	117.1
Total Air Pollutants						
CO_2 10^{11} pounds	138.0	116.9	136.2	128.2	127.1	111.2
CO 10^{9} pounds	6394.7	5870.9	6278.2	6185.1	6371.7	5615.7
NO_x 10^{9} pounds	37.0	32.6	36.4	35.1	34.4	30.8
SO_2 10^{9} pounds	34.7	27.0	31.9	31.1	29.0	24.0
Particulates 10^{8} pounds	229.2	198.9	225.6	206.5	181.8	185.1
HC 10^{8} pounds	137.4	122.7	135.8	133.2	136.5	119.7
Water Pollutants (all in 1000 tons)						
Bases	3.9	3.4	3.9	3.3	2.6	3.4
Nitrates	1.8	1.8	1.8	2.2	1.8	2.2
Other Dissolved Solids	552.8	481.7	533.1	521.7	471.9	438.1
Suspended Solids	98.2	86.2	94.2	93.9	88.3	71.8
Nondegradable Organics	26.6	19.5	23.4	23.3	23.5	17.7
Biological Oxygen Demand (BOD)	69.1	57.5	65.1	65.1	62.3	55.3
Aldehydes	192.1	146.0	170.2	170.9	168.8	131.1
Radioactive Effluents						
Solids, 1000 ft^3	13.1	13.1	13.1	15.9	13.1	15.9
Krypton-85, 10^{6} curies	36.1	36.1	36.1	44.0	36.1	44.0
Tritium, 10^{5} curies	22.2	22.2	22.2	27.1	22.2	27.1
Population Exposure, 1000 man-rem	64.3	64.3	64.3	78.2	64.3	78.2
Heat Dissipated						
Central Sources (Quads)	36.5	33.6	36.5	39.9	36.1	34.1
Decentralized "	69.9	61.1	69.9	65.5	69.3	62.0
Total "	106.4	94.7	106.4	105.4	105.4	96.1
Solid waste, million tons	2569.7	1961.9	2368.0	2304.9	2297.2	1831.1
Land use, million acres	17.2	15.4	17.1	17.5	16.7	15.3
Occupational Health & Safety						
Deaths	209.0	180.0	223.0	199.0	196.0	176.0
Injuries (1000s)	11.2	9.6	11.8	10.7	10.5	9.3
Man-Days Lost (1000s)	540.6	461.0	567.7	511.6	504.7	446.9

TABLE 2. 2000 SCENARIO RESULTS (REF. 1)

	Resources Consumed, Quads (10^{15} Btu)					
	0	I	II	III	IV	V
	Year 2000 Scenario Results—Resources					
Hydroelectric (at 34% efficiency)	3.65	3.65	3.65	3.65	3.65	3.65
Geothermal	1.40	2 40	1.40	6.60	14.93	6.60
Solar	0.00	3.50	0.00	6.59	9.59	4.82
Fusion	0.00	0.00	0.00	0.05	0.05	0.05
Light Water Reactor (LWR)	36.59	16.50	36.59	36.59	10 97	16.50
Liquid Metal Fast Breeder (LMFBR)	0.00	0.00	0.00	3.90	0.00	3.90
High Temperature Gas Reactor (HTGR)	3.90	3.90	3.90	3.90	0.40	3.90
Oil Steam Electric	4.07	2.18	3.77	4.08	2.44	1.88
Gas Steam Electric	2.00	0.00	2.00	2.00	2.00	0.00
Oil, Domestic and Imports	70.54	40.32	37.71	46.47	45.30	19.77
Oil Imports	58.34	20.62	18.01	26.77	20.55	(4.11)
Oil Shale	0.00	0.00	8.00	0.00	8.00	8.00
Natural Gas, Domestic and Imports	15.40	22.80	22.80	22.80	22.80	22.80
Coal (including 1.5 Quads exports)	33.89	22.91	49.77	30.51	45.87	39.11
Coal (million tons per year)	1614	1091	2370	1453	2184	1862
Waste Materials	0.10	6.50	0.10	0.10	0.00	6.50
Biomass	0.00	0.00	1.50	0.00	1.50	1.50
Total Energy Resources (including exports)	165.47	122.48	165.42	161.16	158.01	137.03
Total Cost in Billions of Dollars per year	498.94	325.64	460.52	469.54	396.96	328.74
Average Cost in Dollars per Million Btu of Resources Used	3.02	2.74	2.78	2.98	2.57	2.46
	Year 2000 Scenario Results—Environmental Effects					
Centralized Air Pollutants						
Carbon Dioxide (CO_2) 10^{11} pounds	42.5	26.0	41.0	43.5	34.9	23.7
Carbon Monoxide (CO) 10^7 pounds	62.9	43.0	61.2	65.2	53.2	38.9
Nitrogen Oxides (NO_x) 10^9 pounds	13.0	8.2	12.6	13.3	10.8	7.5
Sulfur Dioxide (SO_2) 10^9 pounds	20.9	13.6	20.1	21.4	17.1	12.4
Particulates 10^8 pounds	76.6	51.3	74.3	78.8	65.1	46.9
Hydrocarbons (HC) 10^8 pounds	3.1	1.5	3.1	3.2	2.6	1.4
Decentralized Air Pollutants						
CO_2 10^{11} pounds	136.4	100.7	134.4	86.8	138.4	106.7
CO 10^7 pounds	9651.3	7677.7	9608.5	8875.6	9603.8	5438.7
NO_x 10^9 pounds	41.8	32.4	37.7	33.1	38.3	13.1
SO_2 10^9 pounds	30.7	16.0	17.5	13.6	20.0	13.3
Particulates 10^8 pounds	301.5	236.8	202.5	181.2	179.3	203.8
HC 10^8 pounds	201.7	163.7	171.8	185.1	173.1	75.2
Total Air Pollutants						
CO_2 10^{11} pounds	178.9	126.7	175.4	130.3	173.3	130.4
CO 10^7 pounds	9714.2	7720.7	9669.7	8940.8	9657.0	5477.6
NO_x 10^9 pounds	54.8	40.6	50.3	46.4	49.1	20.6
SO_2 10^9 pounds	51.6	29.6	37.6	35.0	37.1	25.7
Particulates 10^8 pounds	378.1	288.1	276.8	360.0	244.4	250.7
HC 10^8 pounds	204.8	165.2	174.9	188.3	175.7	76.6
Water Pollutants (all in 1000 tons)						
Bases	9.2	7.4	6.5	5.8	5.2	6.7
Nitrates	6.9	3.5	7.0	7.6	1.9	4.1
Other Dissolved Solids	1005.5	705.2	796.3	889.1	611.8	525.3
Suspended Solids	139.7	100.2	113.2	139.6	104.7	58.2
Nondegradable Organics	39.8	22.8	21.3	26.3	22.7	8.9
Biological Oxygen Demand (BOD)	94.6	58.2	71.9	78.0	65.8	41.1
Aldehydes	281.0	159.6	154.4	188.3	162.6	64.0
Radioactive Effluents						
Solids, 1000 ft^3	51.5	26.8	52.3	57.1	14.3	31.6
Krypton—85, 10^6 curies	135.2	65.9	137.5	142.9	39.1	71.2
Tritium, 10^3 curies	82.2	39.5	83.6	97.8	24.0	53.7
Population Exposule, 1000 man-rem	250.1	128.0	250.1	277.9	69.3	155.8
Heat Dissipated						
Central Sources (Quads)	71.9	43.6	71.9	85.3	50.0	45.9
Decentralized "	93.3	71.3	93.2	68.2	97.0	77.9
Total "	165.2	114.9	165.1	153.5	147.0	123.8
Solid Waste, million tons	4001.8	2392.6	2972.4	2887.7	2974.0	1702.4
Land Use, million acres	27.5	18.0	26.7	28.9	21.7	18.0
Occupational Health & Safety						
Deaths	361.0	239.0	480.0	322.0	435.0	364.0
Injuries (1000s)	18.7	12.4	23.5	16.5	21.5	17.5
Man-Days Lost (1000s)	920.6	608.1	1169.8	808.0	1072.6	875.2

TABLE 3. ENERGY RANKING OF TECHNOLOGIES (REF. 1)

TECHNOLOGY	TERM OF* IMPACT	DIRECT** SUBSTITUTION FOR OIL & GAS	R,D&D STATUS	IMPACT IN*** YEAR 2000 IN QUADS
GOAL I: Expanded the Domestic Supply of Economically Recoverable Energy Producing Raw Materials				
Oil and Gas—Enhanced Recovery	Near	Yes	Pilot	13.6
Oil Shale	Mid	Yes	Study/Pilot	7.3
Geothermal	Mid	No	Lab/Pilot	3.1-5.6
GOAL II: Increase the Use of Essentially Inexhaustible Domestic Energy Resources				
Solar Electric	Long	No	Lab	2.1-4.2
Breeder Reactors	Long	No	Lab/Pilot	3.1
Fusion	Long	No	Lab	—
GOAL III: Efficiently Transform Fuel Resources into More Desirable Forms				
Coal—Direct Utilization Utility/Industry	Near	Yes	Pilot/Demo	24.5
Waste Materials to Energy	Near	Yes	Comm	4.9
Gaseous & Liquid Fuels from Coal	Mid	Yes	Pilot/Demo	14.0
Fuels from Biomass	Long	Yes	Lab	1.4
GOAL IV: Increase the Efficiency and Reliability of the Processes Used in the Energy Conversion and Delivery Systems				
Nuclear Converter Reactors	Near	No	Demo/Comm	28.0
Electric Conversion Efficiency	Mid	No	Lab	2.6
Energy Storage	Mid	No	Lab	—
Electric Power Transmission and Distribution	Long	No	Lab	1.4
GOAL V: Transform Consumption Patterns to Improve Energy Utilization				
Solar Heat & Cooling	Mid	Yes	Pilot	5.9
Waste Heat Utilization	Mid	Yes	Study/Demo	4.9
Electric Transport	Long	Yes	Study/Lab	1.3
Hydrogen in Energy Systems	Long	Yes	Study	—
GOAL VI: Increase End-Use Efficiency				
Transportation Efficiency	Near	Yes	Study/Lab	9.0
Industrial Energy Efficiency	Near	Yes	Study/Comm	8.0
Conservation in Buildings and Consumer Products	Near	Yes	Study/Comm	7.1

*Near—now through 1985
Mid—1985 through 2000
Long—Post-2000

**Assumes no change in end-use device.

***Maximum impact of this technology in any scenario measured in terms of additional oil which would have to be marketed if the technology were not implemented. Basis for calculation explained in Appendix B.

TABLE 4. NATIONAL RANKING OF R, D&D TECHNOLOGIES (REF. 1)

Near-Term Major Energy Systems	Coal—Direct Utilization in Utility/Industry Nuclear—Converter Reactors Oil and Gas—Enhanced Recovery	Highest Priority Supply
New Sources of Liquids and Gases for the Mid-Term	Gaseous & Liquid Fuels from Coal Oil Shale	
"Inexhaustible" Sources for the Long-Term	Breeder Reactors Fusion Solar Electric	
Near-Term Efficiency (Conservation) Technologies	Conservation in Buildings & Consumer Products Industrial Energy Efficiency Transportation Efficiency Waste Materials to Energy	Highest Priority Demand
Under-Used Mid-Term Technologies	Geothermal Solar Heating and Cooling Waste Heat Utilization	Other Important Technologies
Technologies Supporting Intensive Electrification	Electric Conversion Efficiency Electric Power Transmission and Distribution Electric Transport Energy Storage	
Technologies Being Explored for the Long-Term	Fuels from Biomass Hydrogen in Energy Systems	

SECTION IV

PHOTOVOLTAIC SYSTEMS

PHOTOVOLTAIC POWER GENERATION – TECHNOLOGY ORIENTATION

This technology has been applied extensively in small devices for remote applications such as space, buoys, automatic control of street lamps, microwave relay switching, etc. Nearly all of these applications have features in common with the present application (widespread power generation) but none of them has the enormous terrestrial (land use) impact. Further, the capital cost of the solar cells themselves has seldom approached the overriding importance that it will in central electric generating station application. These two related considerations – capital cost and size – force cell efficiency to become an extraordinarily important design parameter.

A photovoltaic central electric generating station will have as its principal components:

- The photovoltaic receivers ("panels," "cells")
- A storage facility
- Power conditioning equipment
- Transmission and switching equipment.

In contrast to conventional steam electric stations, water requirements are trivial and the absence of reject heat eliminates the need for cooling towers.

Photovoltaic Receivers

Photovoltaic solar cells basically are semiconductor devices in which photons are absorbed and charge carriers generated, together with a potential barrier (such as a p-n junction) to separate the charges. These semiconductors must have several very specific properties for photovoltaic application.

An especially critical property is the energy gap, a function of both the elemental composition and the crystal structure. Crystallite size is important. Some materials must be single crystals or annealed coarse grained polycrystals, rather than fine polycrystalline deposits.

Typical photovoltaic materials are elemental or binary inorganic compounds. A few higher order inorganic compounds show promise, and a few organics have been suggested. Very high purity (often with "doping" with a trace element additive) is required.

Materials which satisfy all requirements have seldom been produced in kiloton quantities. Therefore we often lack information on pollution control technology, ecological effects, toxicology and soil chemistry, for example. Current new source performance standards, effluent guidelines, and OSHA regulations may not be appropriate for all candidate compositions. Standard methods of analysis may not be established for ambient air quality, water quality and industrial hygiene situations. (This is now the case for Ga and In.)

At the moment, industry research is moving vigorously in many directions; it is quite unclear what materials will prevail in the immediate term. One expert (Ref. 16) believes single crystal silicon is the most promising, feeling that 18 to 20% efficiency will be practical soon. An ERDA Photovoltaic Branch spokesman (Ref. 6) feels that in the near term emphasis will be on development of thin silicon (100 μm, rather than current 250 μm) devices, but that the intermediate term will see applications of thin polycrystalline films using concentrators. He does not discount the possibility of ternary materials being developed successfully. In the longer term, the same official foresees possible abandonment of concentrators because of prohibitive costs in very large scale application. An Electric Power Research Institute spokesman is certain that polycrystalline CdS will prevail (Ref. 14), but at a maximum efficiency of about 8% (Ref. 16). Some experts believe it will never be cost competitive with silicon (Ref. 16). InSb, Se and group III phosphides have adherents.

For reviews of current technology see Wolf (Ref. 17), Hickok (Ref. 18) and the AIAA monographs (Ref. 19). Wolf reports active current R&D directions in the industry to be:

1. Deposition onto float glass
2. Development of GaAs cells with (Ga, Aℓ)As window layers
3. Improved high temperature performance
4. Cost reduction by efforts in:
    - Replacement of vacuum deposition by spray deposition
    - Using lower cost raw materials
    - Reduction in layer thickness
    - Ribbon production of Si cells to replace discrete crystal growth, sawing and lapping
    - Production of Si ribbons by dendritic growth
    - Chemical vapor deposition of silicon from volatile Si compounds
    - Vapor deposition of Si by crucibleless electron beam heating
    - Development of low cost substrates.
5. Development of concentrators to reduce cell area requirements
6. Development of automated production methods.

The most cursory review of the literature reveals the overriding concern with cost reduction. It is not clear why tradeoffs between cost per unit area and efficiency are not pursued, but most sources resist such compromises. At this time, \$1000/kW (1976 dollars) is considered a tolerable cost. By year 2000, \$1500/kW (1976 dollars) will probably seem attractive (Ref. 16). What is clear is that the ultimately successful materials, and production engineering technology, are almost wholly unsettled for the intermediate and long term.

While it may be premature to institute extensive research on control technology for production of all candidate materials, EPA should maintain close surveillance on industrial practice and close liaison with ERDA's Photovoltaic Branch so that it can anticipate significant trends in the industry with ample lead time. A regulatory strategy probably can be developed without reference to specific elemental constituents.

For the near term, we do know that the following compositions will be used in pilot and demonstration installations:

- Si
- CdS
- CdS-CuS
- GaAs
- (Ga, $A\ell$)As

Requests for proposals and contracts are currently being issued (Ref. 6).

Currently, the Jet Propulsion Laboratory, Pasadena, Calif., is coordinating 27 contracts for solar array manufacture.

Research on CdS cells includes work on spray deposition, accelerated life testing, hermetic sealing requirements and, as always, cost reduction. CdS cells are degraded by atmospheric moisture and oxygen, and by solar warming. The French pioneered improved lifetime of CdS cells by hermetic sealing (Ref. 17).

Currently, there is one U.S. manufacturer of complete CdS panels (Ref. 6): — Solar Energy Systems, Newark, Del. Their product is hermetically sealed and guaranteed for only one year.

It is important to distinguish between the various CdS products. Pigment grade CdS is unsuitable for semiconductor application; its production methods (Ref. 20) may conceivably be adapted to produce semiconductor material, however, Photovoltaic and photosensitive CdS are two different products (Ref. 21). A still more refined research grade (50 ppm) is supplied by Eagle-Picher (Ref. 21) but is used only for laboratory scale studies. Suppliers of CdS material include Fisher Scientific, Atomurgic, General Electric, Sylvania, and Baker and Adamson. CdS devices are supplied by National Semiconductor, Vactac, Clairex, General Electric, and Varian.

Should CdS solar cell panels become economically attractive high demand components, some of these material and device manufacturers may enter the market, possibly with copper, float glass or Mylar™ substrate.

Production and resource data for cadmium products are discussed as environmental effects in a later section.

Varian is a major supplier of GaAs. Manufacture of the compound is currently a very low volume business. Production and resource data are discussed later.

Silicon solar cell manufacturers include Heliotech, Centralab, Solar Power Corporation (Exxon), Sharp (Ref. 22) and Spectrolab (Textron) (Ref. 23). A description of discrete silicon solar cell manufacture is provided by Spectrolab in the Project Independence report (Ref. 23, pp. VII-C-34ff). Continuous methods are described briefly by Wolf (Ref. 17).

Photovoltaic Storage Systems

Coal fired and nuclear steam electric plants can generate on arbitrary duty cycles, and can track demand. Obviously solar generating stations can produce power only during times of adequate insolation. Pumped hydro storage and oil fired turbines for peak shaving are matters of utility economics and network distribution strategy. By contrast, in terrestrial solar energy systems, some form of storage of backup power is an absolute necessity. A common utility system standard of reliability is one day of outage in 10 years. For an independent photovoltaic system to maintain that standard of reliability, prodigious energy storage capacity would be required. The alternative is to require backup power generating capacity from the utility grid in addition to some manageable amount of storage capacity. Unfortunately, therefore, while photovoltaic power may save fossil and nuclear fuel, it would not reduce in the same proportion a utility's capital investment (Refs. 9, 23 and 24).

Another option is to use the solar generating capabilities only for peaking power (at less than full capacity). This would be realistic only in areas where peak demand occurred during periods of maximum insolation (e.g., due to one-shift industry and air conditioning load). Environmentally and economically this is not desirable. Economically this is not practicable and environmentally it does not take complete advantage of all the "clean" solar energy available.

Figure 3 (Ref. 23) displays the relationship between storage requirement and plant capacity factor for one application, imagined to require 12-1/4 hours to 18 hours of storage during non-insolation periods. The amount of fossil fuel backup is not specified. Figure 4 (Ref. 23) displays one candidate interfacing between photovoltaic generators and multiple storage modes.

Storage options are limited; some are summarized in Table 5 and discussed in more detail below. A general review (somewhat dated) appears in Ref. 25.

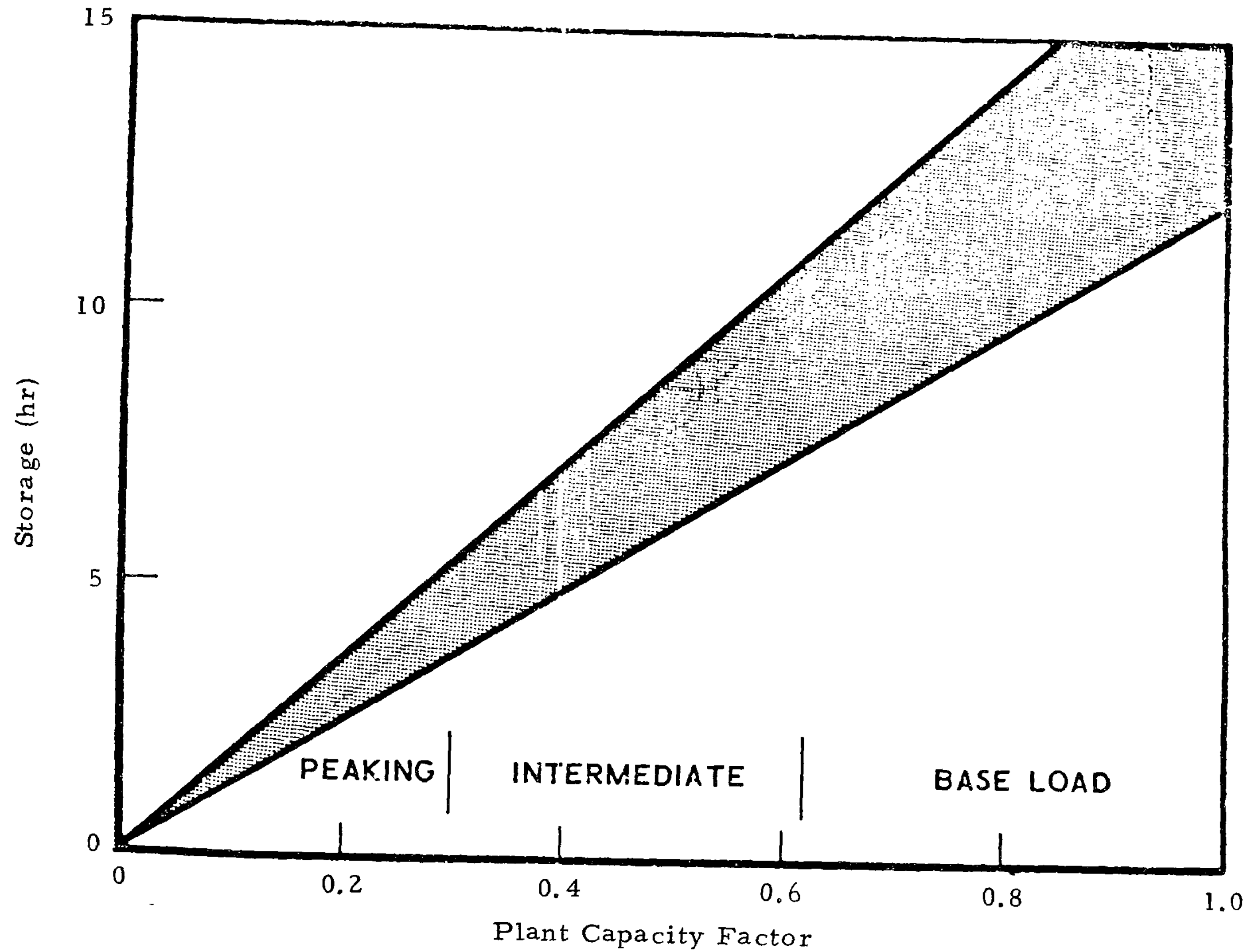


Figure 3. Storage requirements and associated plant capacity factor for capacity displacement.

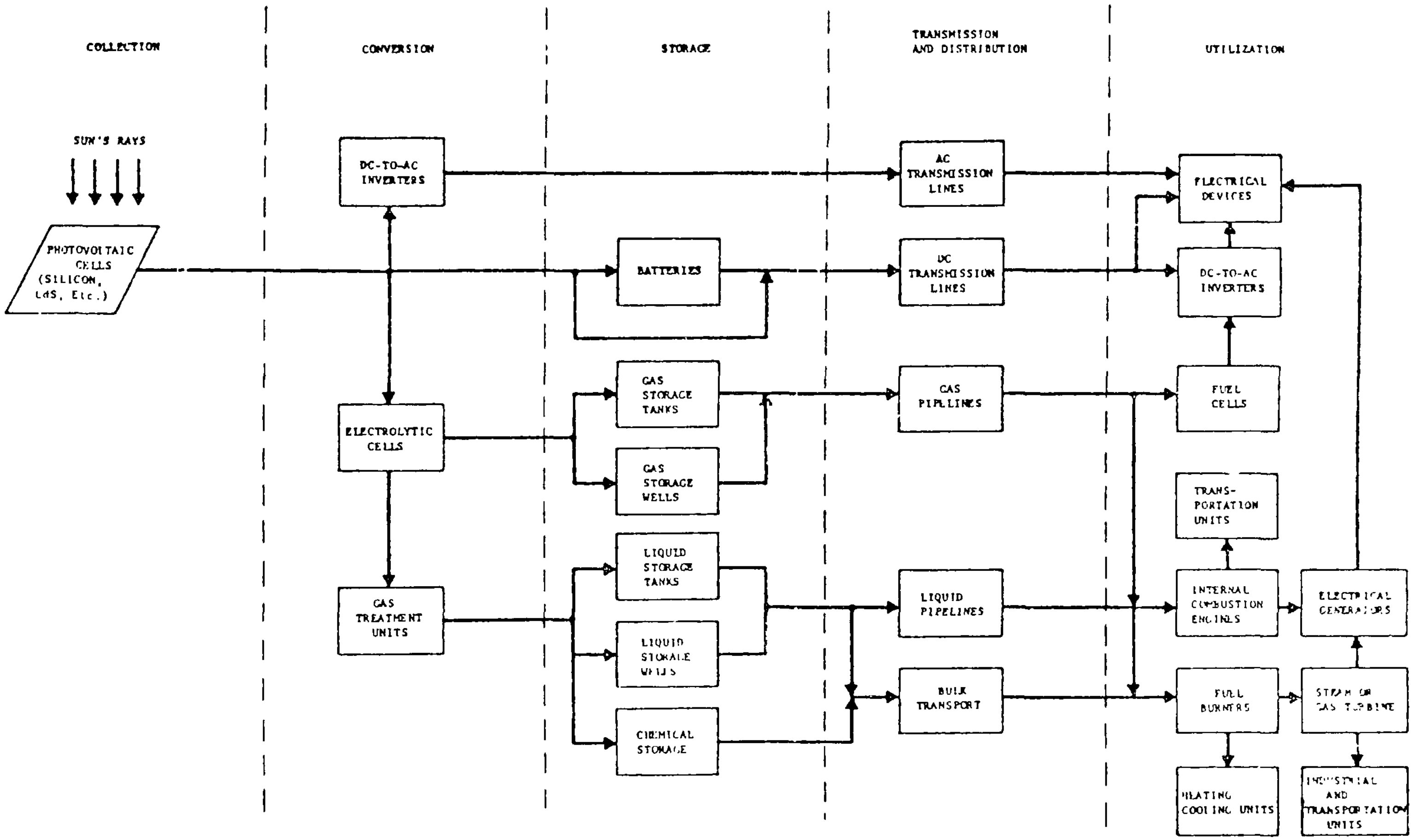


Figure 4. Interfacing photovoltaic – fuel cycles (Ref. 23).

TABLE 5. SUMMARY OF CANDIDATE STORAGE MODES

Item	Pumped Hydro	Compressed Air	Batteries	Hydrogen Cycle	Flywheels	Magnetic
Minimum Economic Size, Utility Application	10^4 MWh	200 MWh	10 MWh	10 MWh	10 MWh	10^4 MWh
Estimated* Costs $/kW	200-300	80-700	180	75-350	100-400	500-600
Expected Service Life (years)	50	20	10-20	30	30	30
Estimated Efficiencies (%)	65-70	45 Primary 70-75 Storage	70-80	50-60	80-95	90-95
Use Fossil Fuels ?	No	Yes	No	No	No	No
Dispersed Capability ?	No	No	Yes	Yes	Yes	No
Resource Limitations	Site Limited	Site Limited	Unknown	None	None	Yes
References**	8, 26	26	8, 19	27, 28, 29	8, 30, 31	

*1970 dollars.

**For all modes, see Refs. 23, 25, 32

1. Conventional pumped hydro storage. This is possible only in terrain of substantial relief and ample surface water. About 2500 to 5000 kWh/acre can be stored. There is no prospect of significantly improving efficiency. Besides large land commitment, there are very serious ecological and aesthetic problems associated with draw down (Refs. 8, 23 and 26).

2. Underground compressed gas experience relates mostly to helium and natural gas. Because auxiliary fossil energy is used, about 4 kW_eh are recovered for every 3 kW_eh in, but the real efficiency is 70 to 75% assuming no gas losses through bedding planes and joints. Obviously this can be used only where geological conditions are favorable, or man made cavities can be exploited (Refs. 23 and 26).

3. Batteries are becoming attractive at least for utility application. The familiar Pb-acid battery is wasteful of lead, which would come into tight supply. High charging rates cause boiling and H_2 evolution, and high discharge rates cause electrode pitting.

   However, newer high temperature storage cells using Na, Li, Cℓ and S capable of high rate discharge are being developed. The requirement that they be heated makes them unsuitable for residential use, but for utility size load leveling they may become very attractive. R&D needs to be aimed at maximizing reliability at lowest cost, even at reduced charge/discharge rate limits (Refs. 8, 19 and 23).

4. Hydrogen cycles: water electrolysis, hydrogen storage cryogenically or as hydride, and oxidation in H_2-air or H_2-O_2 fuel cells. This is especially appropriate for photovoltaic application because the dc power can be used directly. Modular factory construction of components allows add-on just as with the panels. Environmental effects will be discussed later (Refs. 23, 27, 28 and 29).

5. Flywheels today are constructed of metal and/or glass fiber and/or organic fibers. Coupled to a photovoltaic generating system, a flywheel would be driven by a variable speed motor-generator receiving its ac supply from the system inverter. One design features a 100 to 200 ton rotor of 12 to 15 ft diameter rotating at 3500 rpm with a storage capacity of 10^4 to 2×10^4 kWh. It is calculated that a 10^4 kWhr - 3000 kW unit would cost about $325,000 and have an in-out efficiency of 93 to 95% if maintained in H_2 or He. These were 1973 dollars (Ref. 30).

   The AiResearch Manufacturing Company of California (Division of Garrett Corportion) has a U.S. Army contract to supply a 30 kWh flywheel. Their rotor has a Kevlar™ rim, an aluminum hub, and an unspecified web holding the two together. Total mass is 750 lb, yielding 40 Wh/lb. They state they could raise this to ~55 Wh/lb, about twice what can be accomplished with isotropics such as cast steel. By scaling to a cylindrical configuration they feel they can achieve a 10 MWh unit, about the minimum suitable for utility use. Their unit operates in a vacuum of 1 μ - 1 torr at a rim speed corresponding to Mach 3. Discharge from storage is accomplished by "draw down" to 1/2 velocity, corresponding to 75% energy extraction. Maximum practical "draw down" for a flywheel would be 94% extraction (4:1 velocity reduction). Peripheral equipment costs limit extraction (Ref. 31).

Another company in flywheel development work is Rockwell International. They are working with composites (Refs. 8, 23, 25, 30 and 31).

Power Conditioning and Handling

Photovoltaic receivers produce dc power which can be raised to 117 Vdc by appropriate series-parallel connections. Because American transmission facilities and much of the load is designed for ac, inverters are required. These now achieve 95 to 97% efficiency (Ref. 33). The basic technology seems well developed, but there is some interest in further optimizing subsystems (Ref. 19). Especially in smaller dedicated systems, the economics are heavily dependent not only on storage but also on regulator/inverter costs. At least some of the switches, breakers, transformers, regulators, inverters, etc., may be dielectric liquid filled. This could be transformer oils, PCBs or SF_6.

Transmission lines will be required. In the West especially, large amounts of electrical energy are wasted in long distance transmission. There is very definite interest in conserving by grid dispersing solar generating plants nearer to load centers (Ref. 16). This writer has not encountered any discussions of the effect this might have on the current trend to very high voltage transmission. This should be investigated.

Central Station Photovoltaic Generation on Geosynchronous Satellites

This concept, reviewed recently by Williams (Ref. 34), has popular appeal. Figure 5 depicts one conceptual design.

Although several aerospace companies and NASA laboratories have proposed such stations in apparent seriousness and initial design studies have been funded, capital costs are so enormous that our national priorities may prevent construction of such an "installation," regardless of its merits. Table 6 presents one projection of satellite power station deployment.

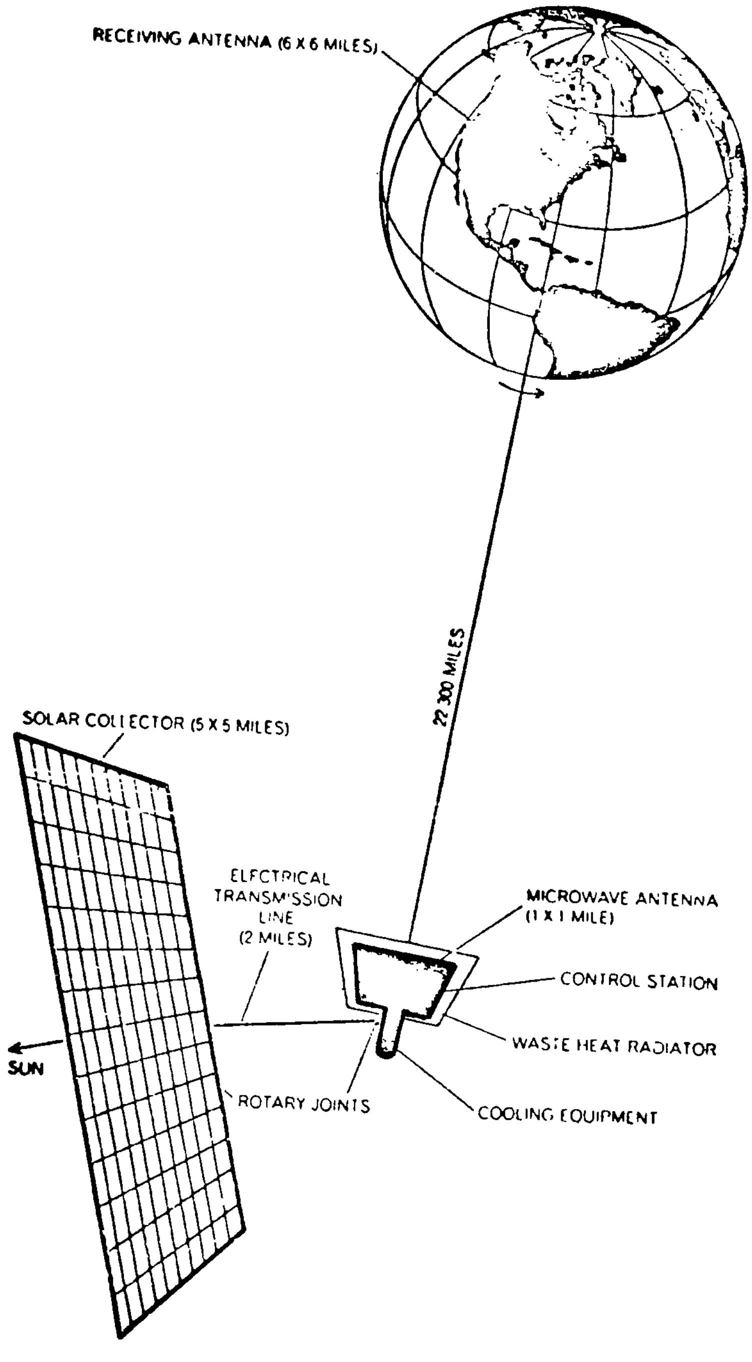


Figure 5. A conceptual 10^4 MW_e satellite photovoltaic power station (Ref. 9).

TABLE 6. PROJECTED SOLAR POWER STATION DEPLOYMENT (Ref. 34)

Time Period	Stations Added	Shuttle Flights* per Year	Cumulative Costs, Excluding R&D ($\$10^9$)	Power Delivered (10^3 MW_e)
1990-94	4	1444	68	56
1995-99	5	1805	149	123
2000-04	7	2527	261	215
2005-09	10	3610	419	345
2010-14	14	4693	635	523
2015-19	17	6137	893	735

*A fully reusable Shuttle with a 277,000 kg payload nuclear tug having 77,000 kg payload from low Earth orbit to synchronous orbit.

Features of this proposal which require attention are:

1. The use of large numbers of shuttle launches (combustion of propellants)
2. The launching from earth of nuclear cargoes, subsequently to be used in space propulsion (consequences of an abort and burn-up)
3. The use of high intensity microwave beams to transmit energy back to earth (physiological and ecological effects)
4. The much reduced quantity of structural material, as compared to terrestrial installations (mitigation of resource depletion).

The geosynchronous satellite generating station has grave direct and indirect environmental problem areas that will be discussed in the photovoltaic assessment section.

It is possible to propose a concentrator-thermal electric satellite power plant; its problems are so similar to the photovoltaic concept that it will not be given separate treatment.

Combined Receivers at Load Centers

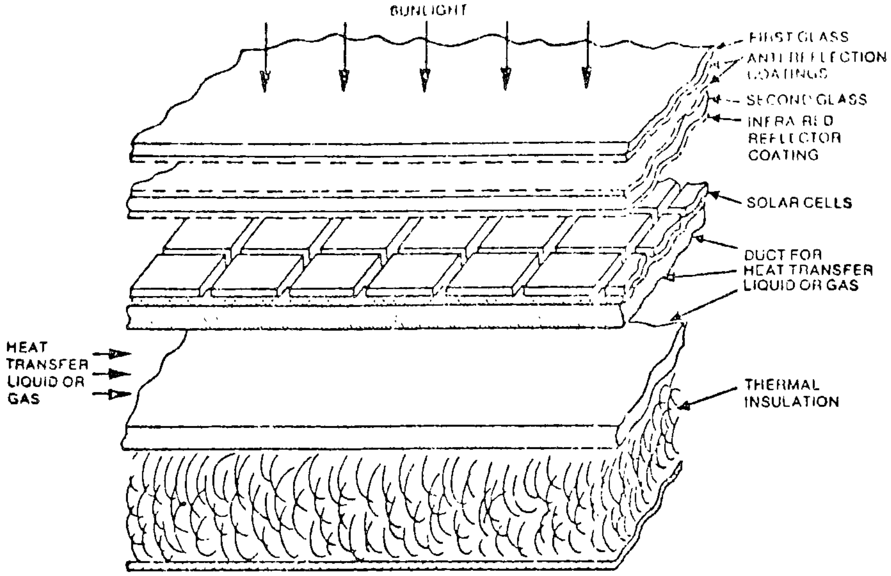
Installations have been designed which combine a photovoltaic receiver with a flat plate thermal collector, achieving a combined efficiency which is quite high at no increase in area covered. See Wolf (Ref. 17) for a discussion.

Most buildings require both heating-cooling and electricity. By having the solar photovoltaic array form the absorber surface of the thermal collector, component cost is reduced by multiple use, and up to 60% of the total available solar energy is absorbed (Figures 6 and 7).

This system does not appear to have any adverse direct or indirect environmental effects not discussed in the photovoltaic and flat plate sections. On the beneficial side, there is a real saving in land or building area, and some material saving. No further discussion of this concept seems to be required now.

Concentrator Photovoltaic Systems

GaAs is more temperature resistant than other photovoltaic semiconductors. Consequently, it is possible to place this photovoltaic material at the focus of concentrator mirrors of various configurations. Substantial reductions in GaAs requirements result — roughly by the same factor as the concentration ratio. One thousandfold savings are conceivable with this scheme (Ref. 11). The environmental consequences of this kind of installation will be discussed in the concentrator chapter and in the photovoltaic materials resource section.



Photovoltaic solar array can be mounted inside a thermal flat plate collector for combination heating and photovoltaic power systems.

Figure 6. Photovoltaic-thermal combined collector (Ref. 17) (Reproduced by permission of author).

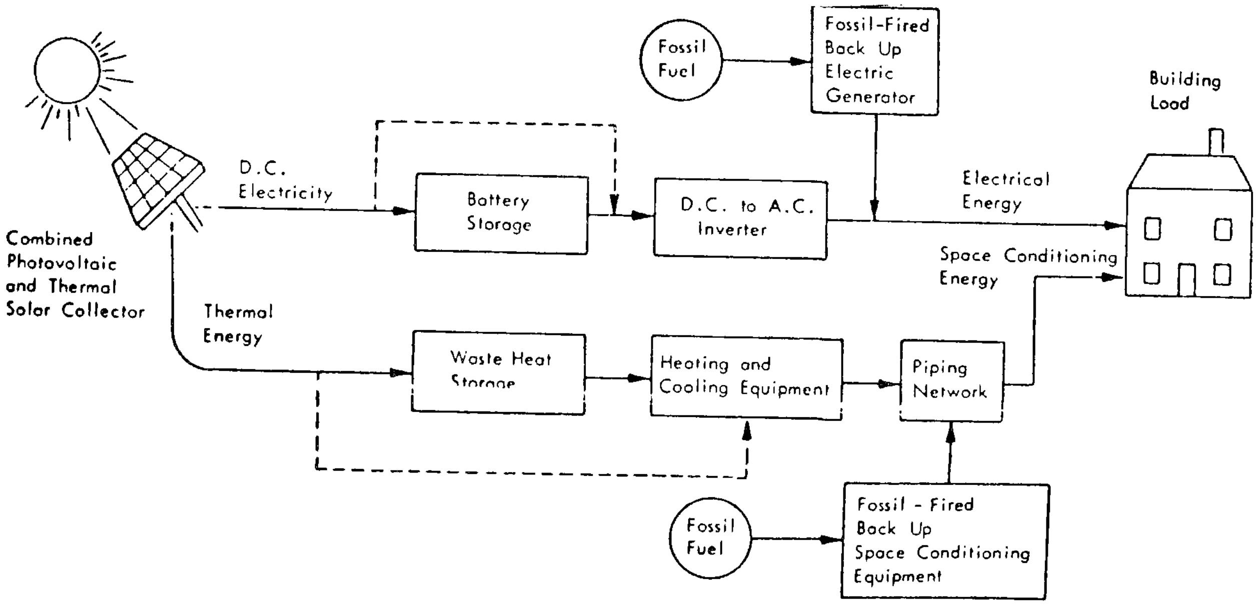


Figure 7. Combination photovoltaic and heating-cooling system (Ref. 17) (Reproduced by permission of author).

ENVIRONMENTAL ASSESSMENT – PHOTOVOLTAIC SYSTEMS

Siting and Grid Dispersal

Most writers on the subject assume that major utility solar installations will be located in the U. S. Southwest, in areas of highest insolation. It is important to distinguish between total insolation and direct insolation. Concentrator systems, including photovoltaic, can use only the latter (Figure 8).

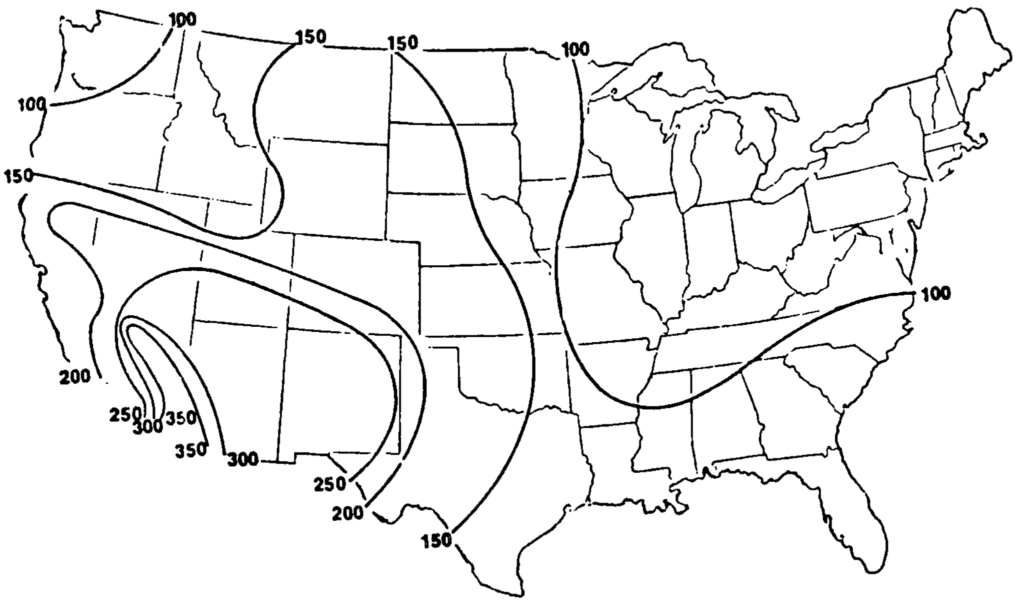


Figure 8. Isopleths of mean daily direct solar radiation, Langleys/Day (Ref. 35) (1 Langley = 1 cal/cm^2 = 3.62 Btu/ft^2)

Flat plate systems, including photovoltaic panels, use both direct and diffuse radiation (Figure 9). These figures reflect both the solar radiant intensity reaching earth at each latitude, as well as meteorological effects such as cloud cover. They may not contain corrections for interruptions due to dust storms.

Season-to-season variations cannot be leveled by storage. In regions where season-to-season variations are large (Table 7), non-solar generating facilities must be available during the low-insolation months.

Grosskreutz (Ref. 35) has described criteria and procedures for siting solar steam-electric plants. Aside from concern for water availability, his study should apply to photovoltaic panel systems. In addition to several legal, social, and institutional matters, his criteria include:

TABLE 7. SOLAR RADIATION AT SELECTED LOCATIONS IN THE UNITED STATES DURING 1970*

Location	Average Total Daily Insolation (Btu's per square foot per day)**												Annual Average
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Seattle-Tacoma, Washington	278	688	1069	1354	1950	2065	2105	1750	1217	747	370	229	1152
Fresno, California	710	1117	1709	2205	2609	2579	2576	2412	2050	1425	910	614	1743
Tucson, Arizona	1110	1391	1750	2202	2435	2449	2190	1983	1735	1587	1221	870	1745
Omaha, Nebraska	777	1110	1284	1576	1939	2165	2002	1865	1280	944	581	596	1351
San Antonio, Texas	862	1103	1432	1506	1906	2083	2176	2057	1587	1388	1310	784	1516
Lakeland, Florida	1029	1436	1480	1983	2079	2042	1883	1680	1639	1436	1302	1169	1597
Atlanta, Georgia	873	1203	1288	1635	1991	1854	1917	1628	1591	1021	955	714	1389
Burlington, Vermont	581	781	1088	1384	1447	1758	1587	1835	1195	759	444	448	1109

*Source: Commerce, 1970: Vol. 21, Nos. 1-12.

**1000 Btu/ft^2-day = 276.24 Langley/day. 1 Langley = 1 cal/cm^2.

Figure 9. Distribution of solar energy onto a horizontal surface. (figures give solar heat in Btu/ft^2 per average day; 1000 Btu/ft^3 = 276.24 Langleys) (Ref. 9).

- "Avoid dry lake playas, depressions, sand dunes, and areas of uncompacted sand"
- "Avoid seismic faults (this would be much less important in these applications, not requiring "power towers.")"
- "Avoid proximity to airports and flight corridors." (His concern is not explained. Presumably highly reflective surfaces covering many square miles could be visual flight hazards to flight personnel, but perhaps no more so than large bodies of water.)
- "Seek relatively flat areas with good drainage. Slopes which face south are acceptable, especially for central receiver system configurations." (It is not clear why flat panel arrays cannot be placed on slopes with equal ease. To reduce subsequent erosion of terrain disturbed during construction, however, slopes should be avoided.)
- "Access..... with a minimum of secondary road improvement or spur construction" (Almost unique among power plants, most of the construction of these installations will be modular, with fabrication occurring in remote factories. Construction will place unusually heavy demands upon surface transportation.)

Several writers have emphasized that the insolation, meteorological and terrain criteria will necessarily force siting of solar power stations in regions of desert biome and uniform ecological characteristics.

An important feature of photovoltaic siting relates to the very small economies of scale (Ref. 5). This means that the size of a unit may be decided by economics of peripheral equipment, transmission equipment, access preparation, etc.

An EPRI spokesman (Ref. 14) has addressed the security aspects of grid dispersed stations — physical security is a problem in grid dispersed systems, but the problem can be solved. System security favors dispersed installations. He too emphasized that reduced transmission and distribution costs, reduced capital investment, and reduced peak demand problems all favor serious consideration of grid dispersed solar power stations.

The Auburn University Summer Fellows program final report "MEG-ASTAR," presents some interesting observations on siting related to institutional and social matters, which can be quoted here as usefully as later (Ref. 36).

> "The diffuse nature of solar energy allows the generation of solar power to be widely distributed. The 100 GW capacity suggested for the year 2000 in the previous section would involve roughly 450 square miles, but this will not be sited on a single 21 mile square. There are several advantages to a distributed source. Transmission line losses are reduced, the need for more transmission line corridors is eliminated, and individual plant failures are felt only locally. Also, there may be a positive social impact associated with decentralized power sources. The tax and cost structure and responsibility associated with smaller, local power plants provide a healthy social climate and a feeling of "oneness," belonging and pride in the community. The size distribution of American cities shows a great many communities of 10,000 to 13,000. If average solar insolation figures are used, a solar plant (photovoltaic or thermal) of about 0.1 square miles and some form of storage (batteries, flywheels, electrolysis/fuel cells or thermal) could supply all the electrical power needs for a community of 12,000. This corresponds to an average power demand of about 7 MW day and night, summer and winter. Clean air is especially desirable in residential areas; pollution from power generation would be completely eliminated. In defense of the existing centralized utility operation it would be noted that operating costs usually go up with decentralization. On the other hand savings in transmission line and conventional fuel costs may offset the higher operating costs."

Szego (Ref. 26) states that transmission costs account for about one third of our electricity costs. This suggests that very careful analysis needs to be applied to the economics of grid dispersed stations near load centers in the Southwest. Such dispersal of solar generating capacity would also reduce transmission losses and thus reduce dependence on fossil and nuclear fuels in some degree.

Szego has also commented on the urgency of developing siting procedures, and related matters:

> "Siting a Major Stumbling Block. Siting decision methodology must promptly be developed. The struggle invariably joined relative to siting of power plants or pumped storage facilities has become reflex rather than a rationally motivated, selective opposition-protagonist dialog. Ecologically-motivated resistance to siting selections is inevitably seriously counterproductive. The longer a plant is delayed, the more the electrical utility industry turns to gas turbines, which have lower efficiency, and thus create about 75 percent more thermal and gaseous pollution than larger steam plants, and use more fossil fuel in the same proportion. This is not the goal of the siting resistors, but it is achieved nevertheless."

Direct Effects

Surface Water Effects and Thermal Pollution: In much of the Southwest, especially, surface water and ground water are in exceedingly short supply. This makes particularly cogent the requirement that the quality of U. S. waters not be degraded and that States and Federal facilities have water quality management plans (Ref. 37).

An outstanding virtue of photovoltaic panel receiver systems is their trivial water requirement:

- No thermal pollution occurs because no cooling water is needed.
- Because no cooling towers are needed there are no problems with biocides, slimicides, detergents, anticorrosion agents, etc., in blowdown or once-through waters.
- At least at present, photovoltaic panels are hermetically sealed. This avoids discharge of eroded CdS or other toxic semiconductor materials onto the land and into the surface waters under normal operation.
- It is still uncertain whether dust accumulations on panel surfaces will create unacceptable transmittance losses. Pilot studies have not often encountered serious transmittance problems ascribed to dust. Possibly periodic or occasional washing will be needed. This would have to be done in situ using some kind of automated downwash system, and on a batch work basis to avoid excessive water demand. We have no information relative to possible detergent demand in this operation.

Groundwater: Large areas of the Southwest have cavernous limestone bedrock (Figure 10). A feature of such terrain is its ability to transport pollutants unexpectedly and rapidly to remote areas by direct conduit transport in the vadose groundwater (Ref. 38).

Figure 10. Principle known regions of cavernous limestones in the contiguous U.S.

Initial land grading could conceivably disturb the subsurface geohydrology. Although the desert areas do not receive much rainfall per unit area, very large areas will be involved.

If the recharge area for an existing vadose groundwater system were almost wholly under such a disturbed area, distant aquifers could be affected. Figure 11 displays the relative paucity of usable aquifers in the Southwest. Extreme care must be used to avoid degrading in any way the quality and the availability of the waters of the Southwest. This will be far more difficult in the case of steam-electric concentrator systems, discussed later.

New towns will arise in rather inhospitable areas to accommodate construction and operating personnel. These communities will require potable water, sewerage, and solid waste management services. Unusually careful regional planning will be required in order to supply these needs without infringing on appropriated surface waters and degrading surface and subsurface

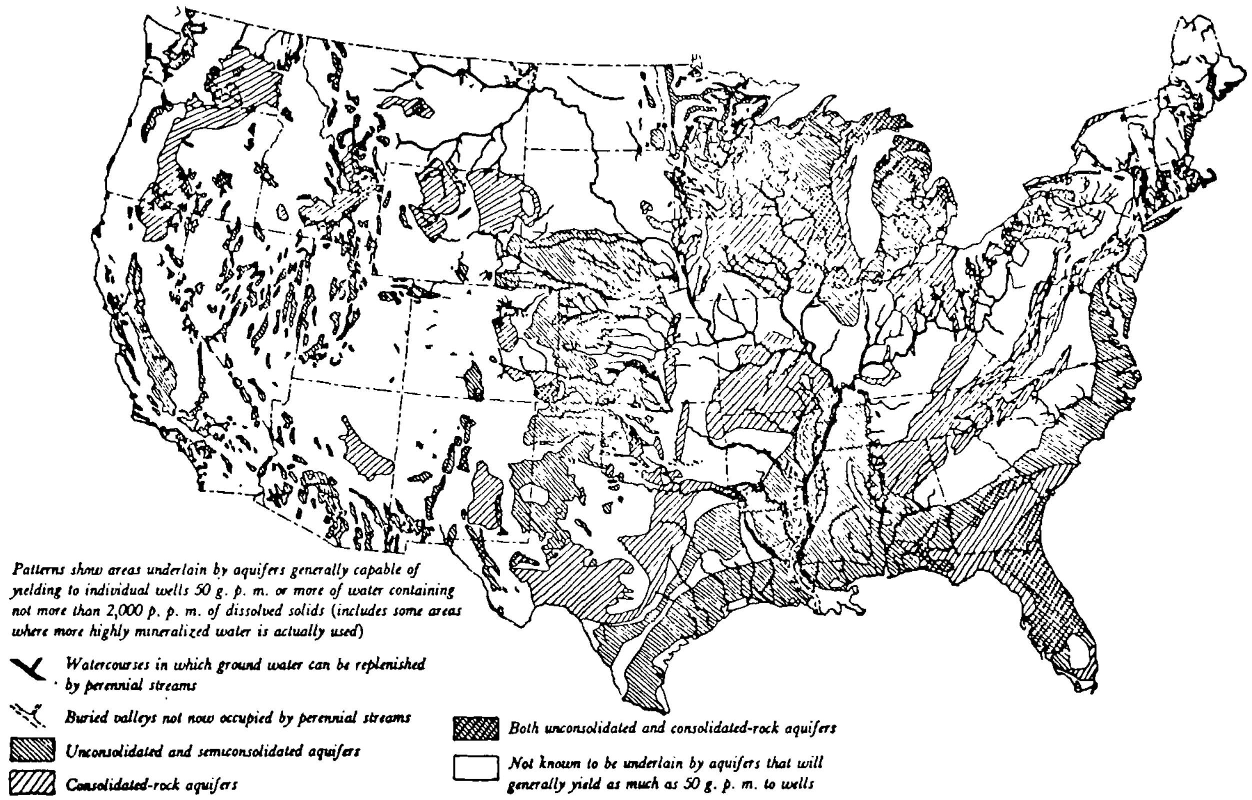


Figure 11. Groundwater areas in the U.S. (Ref. 39).

waters. ERDA is not yet addressing water problems with much intensity (Ref. 12).

Grosskreutz (Ref. 35) has suggested that water might be brought to these developments in canals or pipelines. He is almost alone in alluding to the effects of groundwater pumpage on aquifer drawdown. Even if supporting communities are supplied by well water, it does not seem likely that their demands will be large enough to cause surface subsidence. That possibility should be considered by site selection teams, however.

Land Use: Among direct effects of a major solar electric installation, land use related effects are certainly the most obvious, if not necessarily the most adverse.

The upper theoretical limit for solar electric conversion and land use efficiency would correspond to about 2 mi^2/GW_e (Ref. 36). To expect a utility to achieve this power generation "density" would be unrealistic. In any event, land acquisition costs may be too trivial a fraction of installed cost to provide much incentive for stringent economics in land use. Cost of construction and maintenance argue for reduced area density of receiving panels. More realistically we should expect a 1 GW_e photovoltaic plant to occupy 4.5 to 17 mi^2 (Refs. 7, 23 and 36). The AEC figure (Ref. 9) of 30 mi^2/GW_e seems spurious and a figure of 660 mi^2/GW_e (Refs. 23 and 36) which has been perpetuated seems to be due to an improper extrapolation of data for residential systems.

Referring to Table A-1, we find a year 2000 Scenario III projection of 50 GW_e solar-electric. Assume 40% of this is photovoltaic; if we accept the Project Independence area density value of 7.7 $mi^2/1\ GW_{pk}$ (Ref. 23), we project a land use of 154 mi^2. This would not occupy a single 12.4 x 12.4 mi site (cf. our earlier discussion on grid dispersal). Project Independence (Ref. 23) projections are more optimistic than ERDA-48 projections, suggesting photovoltaic power systems could supply about 191 GW_{pk} in a "business as usual" schedule and 1100 GW_{pk} in an accelerated schedule. Table 8 summarizes some land use data.

TABLE 8. YEAR 2000 PHOTOVOLTAIC POWER CAPACITY PROJECTIONS AND CORRESPONDING LAND COMMITMENT

Forecast	Total Capacity (GW_e)	Land Area (mi^2)	Total Contiguous U.S. Land Area (%)
ERDA-48* Scenario III x 40%	20	154	0.005
Project Independence** Business as Usual	191	1473	0.05
Project Independence** Accelerated	1100	8492	0.27

*Ref. 1.
**Ref. 23.

The densities used above are significantly less than the densities theoretically possible. This is not only because production panels cannot perform to laboratory standards, but also because in a real installation the panels would not be planted side-by-side in tile fashion. First, they would be inclined at the latitude angle above horizontal or perhaps a few degrees more (Brownsville, Texas is about 19°30'N, Albuquerque, New Mexico, about 35°N, and Boulder, Colorado, exactly 40°N). Furthermore, space is needed for: (1) construction and service roads; (2) transmission lines; (3) power conditioning facilities; (4) energy storage facilities; (5) substations; (6) maintenance buildings; (7) control room and office buildings, and (8) access roads and parking lots, etc.

Many of these auxiliary facilities will have to be distributed throughout the field of panels. To avoid shadowing the receiving surfaces, the auxiliaries will have to be low. For example, perhaps transmission lines would be in trenches, and power conditioning and storage modules in low block buildings in small islands distributed throughout the field. Manway corridors will be needed between rows of panels; at least every second manway will have to be at least wide enough for a pickup truck. Near term cost tradeoffs will dictate even greater spacing to avoid self shading. Thus, perhaps the visual appearance of such an installation would approximate a large and orderly storage yard.

To help put these area considerations into perspective: all the electrical power used in the U.S. in 1972 could have been generated in 3000 mi^2 in Arizona at a generating efficiency of 12% (Ref. 24). The 2.1 GW_e "Four Corners" coal fired powerplant of Arizona Public Service is reported to have already under lease for coal stripping more land than would be needed to construct a 1 GW_e solar plant using 6.2 mi^2 of collector surface (Ref. 7).

Figure 12 quantifies this. It is adapted from an AEC comparison (Ref. 9), which had claimed a 1 GW_e solar electric plant would require 30 mi^2 of land. This was in the solar assessment in the "alternatives considered" portion of the LMFBR proposed final E.I.S. The AEC "Range for Coal Surface Mined" has not been altered. The accompanying text does not elaborate on the input assumptions, or whether indirect land disturbances were included. The comparison looks extremely favorable to solar development, even granting that some strip mines are being reclaimed.

Visual Effects: The appearance of a photovoltaic plant has been described earlier. Environmentalists who enjoy the wildness and openness of the desert would probably prefer no development. At the same time, excellent arguments have been advanced that among the few obvious alternatives is more coal mining (Ref. 40). Solar electric development appears to be less destructive of aesthetic values than coal mining and preparation, without the directly identifiable air and water pollution impacts. Further, photovoltaic plants will have no high structures other than departing transmission lines, common to all electric generating facilities.

Terrain Effects: This subject appears to have two aspects: terrain modification during construction, and during operation. Additional indirect effects will be discussed in a later section of this report.

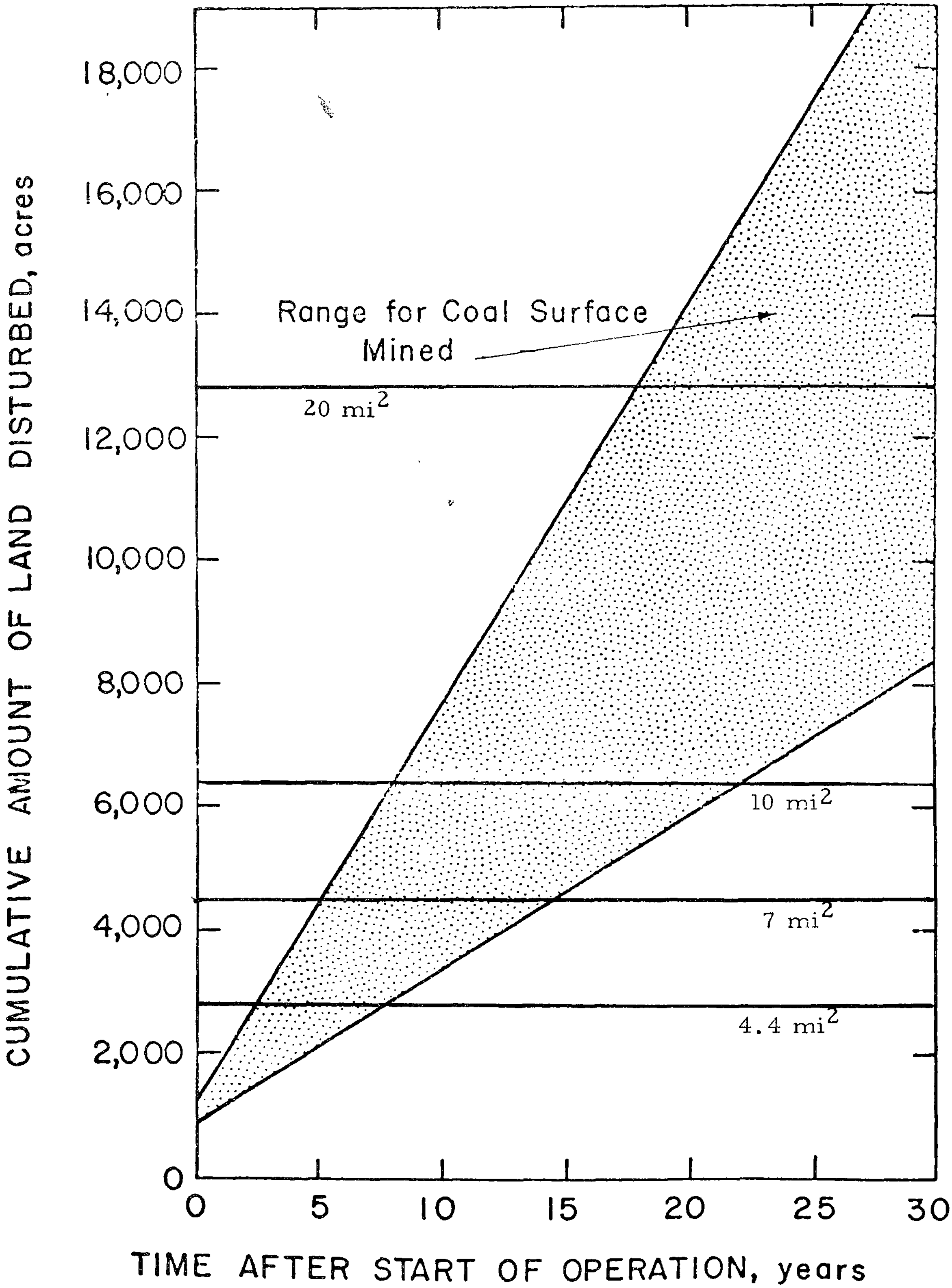


Figure 12. Comparison of land disturbed for 1 GW_e coal-fired steam electric plant and typical areas for 1 GW_e solar plants (Ref. 9).

Construction Phase: Most conceptual designs envision photovoltaic receiving panels to be placed on level or gently sloping terrain. Grosskreutz (Ref. 35) recommended this in his siting study. Candidate sites are unlikely to be forested. Consequently, only minimal grading and land clearing are likely.

Many of the candidate sites are in desert areas in which arroyos and dry washes are common. Most especially in sites near mountains, these should not be obstructed. Plant layout must be preceded by an understanding of surface hydrology after storms in the mountain watersheds supplying the arroyos.

Solar panel supports presumably will require footings to be poured, but no foundation excavations. There will be a few buildings of conventional construction, and heavy peripheral equipment which will need to be supported by concrete pads.

Operating Phase: There is a potential for water run-off to cause erosion. Panels or arrays of panels of perhaps as much as 100 m^2 individually, will be inclined at perhaps 35deg above horizontal. During infrequent rainfalls, water will run off these impervious surfaces and could strike the ground with substantial velocity. Some provision must be made to decelerate and distribute run-off water onto the ground to avoid erosion.

Agriculture and Terrestrial Ecology: The following passages are quoted from Ref. 9:

"The land now most likely to be used for central-station thermal conversion or photovoltaic solar plants is in the desert and semi-desert Southwest. Some open-range grazing is done on parts that receive a little rainfall. The vegetation is so sparse (chiefly creosote bush and white bur sage, with lesser amounts of saltbush paloverde, catclaw, and cactus) that the land is not very valuable as graze land (Ref. 41). During the winter and summer rains, the desert usually has a lush cover of annual grasses and forbs and is valuable for grazing for a short period. This land is used for very little human habitation or industrial activity except in the cities. If solar power plants were developed, the economic value of adjacent land would undoubtedly increase but aesthetic values might be reduced.

"To develop land for large solar power plants will necessitate the construction of roads and sites for the solar collectors.

This process may involve destruction of much of the local ecosystems. On the other hand, some persons believe that if half the land were shaded, it could be greatly improved as graze land. This modification would require new plantings and management. Before a judgment could be made on the feasibility of this agricultural use of the land, agricultural research would be necessary.

"Shade itself would have a significant effect on the vegetation. Plants indigenous to the desert require high-intensity sunlight. Some ecologists believe that these plants would die out in shaded areas (Ref. 41).

"Many species of mammals, reptiles, amphibians, birds and invertebrates are in these desert regions. Some are threatened species. The construction of large central station solar plants might upset the ecological equilibrium, but to predict the changes that would occur in animal populations is difficult. The extent of change would obviously depend on the number and size of plants constructed."

Clearly there is some potential for multiple use, which can be evaluated by research. The development we are discussing is to take place over several decades, and very slowly at first. Ample opportunity exists to perform the agricultural and ecological studies needed.

Evaluations of ecological effects must be weighed against known effects of fossil fuel fired power plant emissions. The latter knowledge is also at a rather primitive stage. Most of the studies of vegetation injury due to air pollution, for example, were performed in the North, the East and the Southeast. These studies are not relevant to the ecologies of Southwestern deserts or high arid plateaus. Our knowledge of the environmental impact of conventional generating facilities in these ecosystems needs to be upgraded. Even back-up facilities (perhaps older less efficient coal fired plants which would otherwise have been retired), will produce SO_x and atmospheric particulates in an ecologically signficiant quantity.

Air Pollution: No potential for air pollutant emissions from photovoltaic panels seems to exist. Environmental effects of storage options are discussed in a later subsection.

Power conditioning and other peripheral equipment may contain PCBs or SF_6. SF_6 is non-toxic, but had some potential for use as a sensitive spiking agent for plume tracing (Ref. 42). This application may be eliminated if accidential releases continue to occur.

PCBs are known toxic agents which concentrate in aquatic organisms and are transmitted up food chains. Their fates and ecological effects in desert biome should be determined. Possible atmospheric releases of PCBs must be prevented during fabrication, installation, normal operation, and maintenance activity.

Transmission Line Effects: There have been reports that electromagnetic radiation from power lines can affect animal growth (Ref. 43) and can affect the earth's magnetosphere (Ref. 44). Atmospheric ozone is commonly thought to be noted near high voltage transmission lines.

These effects, if real, surely must be independent of mode of power generation. Further, to the extent that solar generators are grid dispersed, lower transmission line voltages will be practical. It seems probable that solar energy development has some potential for reducing such effects below what could occur if conventional coal or nuclear fueled plants were introduced in the same general regions. Conversely, intensive solar development would introduce such effects into some specific desert locales not previously exposed. Field research would be needed to establish the reality and extent of the effects, if any, and the mitigating technology, if required.

Visual effects, and right-of-way construction effects, may be very severe, as with any utility network installation. The severity of these transmission line impacts, however, cannot be evaluated effectively in a non-site-specific study.

Weather Modification — Direct and Indirect — All Technologies:* Coal and nuclear fueled power plants are only 30 to 40% efficient. As a consequence, prodigious amounts of reject heat are released to earth's atmosphere by steam electric generating plants and heating plants. The Project Independence Task Force examined this problem in great detail (Ref. 23, pp. A-II-iff) primarily on a global scale. The task force conclusions are that human influences on the global heat balance have so far arisen from five major sources, of which three are related to fossil fuel combustion:

1. Particulate Emissions
   Fuel combustion, industrial activities and natural sources combine to emit atmospheric particulates which probably produce a net cooling by reflecting or scattering sunlight away from earth.

2. Carbon Dioxide Emissions
   Fossil fuel combustion has created a 9% CO_2 increase since 1870, and will produce a projected 30% CO_2 increase by year 2000. Atmospheric CO_2 produces a net heating effect by absorption of solar radiation.

3. Direct Release of Heat

They state that "CO_2 emissions appear to be the most likely effect to cause global climate changes in the long run."

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*Much of this discussion would be appropriate in the section on indirect effects. However, it seemed convenient to consolidate the discussion. Likewise, concentrator and flat plate effects are included here.

To the extent that solar power generation displaces fossil fuel combustion, the developing industry will have a beneficial effect in decelerating our inadvertent climate modification. The task force position, written by R. S. Greeley of MITRE Corporation (Ref. 23 loc. cit.) is aptly summarized:

> "The use of fossil, nuclear and, to a lesser extent geothermal energy sources throughout the world at rates possible to be attained before the year 2100 could cause an increase in average global temperature. The size and effects of such a temperature increase have not yet been calculated with any degree of certainty.
>
> "The use of solar energy instead of "stored" energy sources would avoid the problems of waste heat release and carbon dioxide emissions and thus avoid the possibility of such a global temperature increase. However, the large areas needed for solar energy collectors could pose a problem in land use and could affect climate through changes in energy distribution patterns.
>
> "More extensive measurements and calculations of global climate changes are needed in order to understand the causes of such changes, particularly from human activities, and to predict their impact on the earth and on human society." (Emphasis added.)

The impact of solar collectors on heat balance is summarized schematically in Figure 13. The position adopted by many authors is that almost the same quantity of solar energy is returned to earth's atmosphere and to space, with, as without, solar collection, but that the geographical location of such return is altered. This is an oversimplification. A significant fraction of man's energy use is dedicated to unreversed enthalpy increase — for example, in reduction of bauxite to produce metallic aluminum. This is a very electric energy intensive industry. However, the point is valid that fossil fuel combustion and nuclear fission release stored energy not previously part of earth's heat balance in this geological era.

Because solar plants are likely to be distributed, we are unlikely to create giant "heat bubbles" over thousands of square miles of consolidated solar collector. Because solar development is starting out small, we have an opportunity to learn how serious heat balance effects may (or may not) be before we are irrevocably committed to enormous consolidated projects.

Solar thermal (steam electric) plants share with coal and nuclear plants an efficiency of about 30 to 40%. The reject heat is likely to be discharged in cooling towers. Sites in the desert southwest may not have adequate unappropriated water; dry cooling towers may be necessary. If wet towers are used, drift and fog will also result, but will dissipate more rapidly than in, say, Baltimore. (Cooling tower chemicals will be released to a fragile ecology with blowdown, fog, and drift.) As a consequence, solar

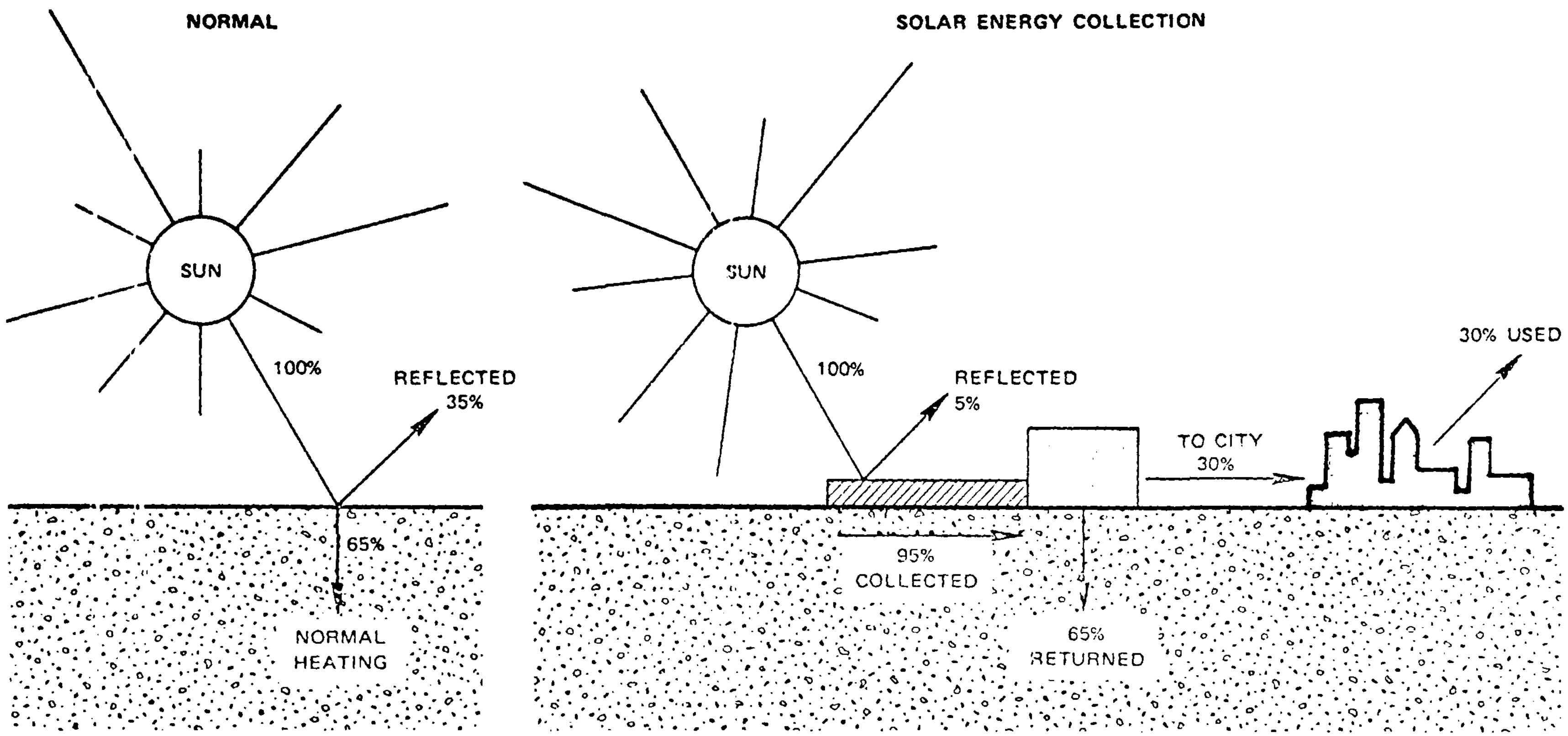


Figure 13. Thermal energy balance (Ref. 7).

steam electric plants will create the same kind and quantity of atmospheric thermal effects as the equivalent conventional plants.

The potential for local weather modification due to the artifically altered humidity needs to be investigated. It is possible also to imagine some rather unusual flora developing in the "moist desert" created adjacent to a cooling tower! Furthermore, the utility companies have a vested interest in learning about local weather modification, because the performance of the solar collectors or concentrators is related to cloud cover, light scattering by haze, etc.

Urban roof top and sidewall flat plate collectors may be expected to alter the heat balance of a city if they become common features. The extent to which they will alter the urban "heat islands" or "bubbles," and therefore the cloud cover, precipitation, mixing depth, and frequency of stable inversions is apparently unknown. This effect needs to be studied; it seems capable of computer simulation, at least with quite simple urban models. Probably some useful insights could be gained in laboratory modeling, also.

The entire complex of interfaced effects related to altered vertical temperature gradients is likely to depend on several geometrical and meteorological parameters in a feed-back loop sufficiently subtle as to preclude prediction prior to well designed research.

Among these parameters we have to include roughness. Advection, mean winds, and turbulence in urban environments are extraordinarily complex problems. Researchers in this area have found that laboratory simulation in meteorological wind tunnels is often necessary (Ref. 45), and frequently successful.

In Figure 14 the boundary layer effect of modest roughness is displayed. A large concentrator installation with many power towers of 200 to 300 meters height, and many heliostats projecting several meters above the mean ground plane might approximate a woods or small town in its meteorological effect. Cermak (Ref. 46) believes there is some potential for problems if large areas are used. He believes research here could be a signficiant aid. He wonders about effects on downwind urban areas. The problem should be amenable to both model studies and computer simulation. Cermak suggests examining the internal boundary layer and on up, studying the effects of stepwise changes. He feels there is some potential for optimizing solar receiver field and structure configurations. A substantial applicable literature now exists in both the hydraulic and the meteorological literature.

Auer, at Laramie, has been participating in the METROMEX studies in the St. Louis area. Among his observations (Ref. 47):

- Most meteorological anomalies are associated with land use changes.
- When vegetation cover is $\leq 5\%$, or when there is an 80 to 90% surface change, the meteorological changes occur not just at the surface, but up through the mixing layer.

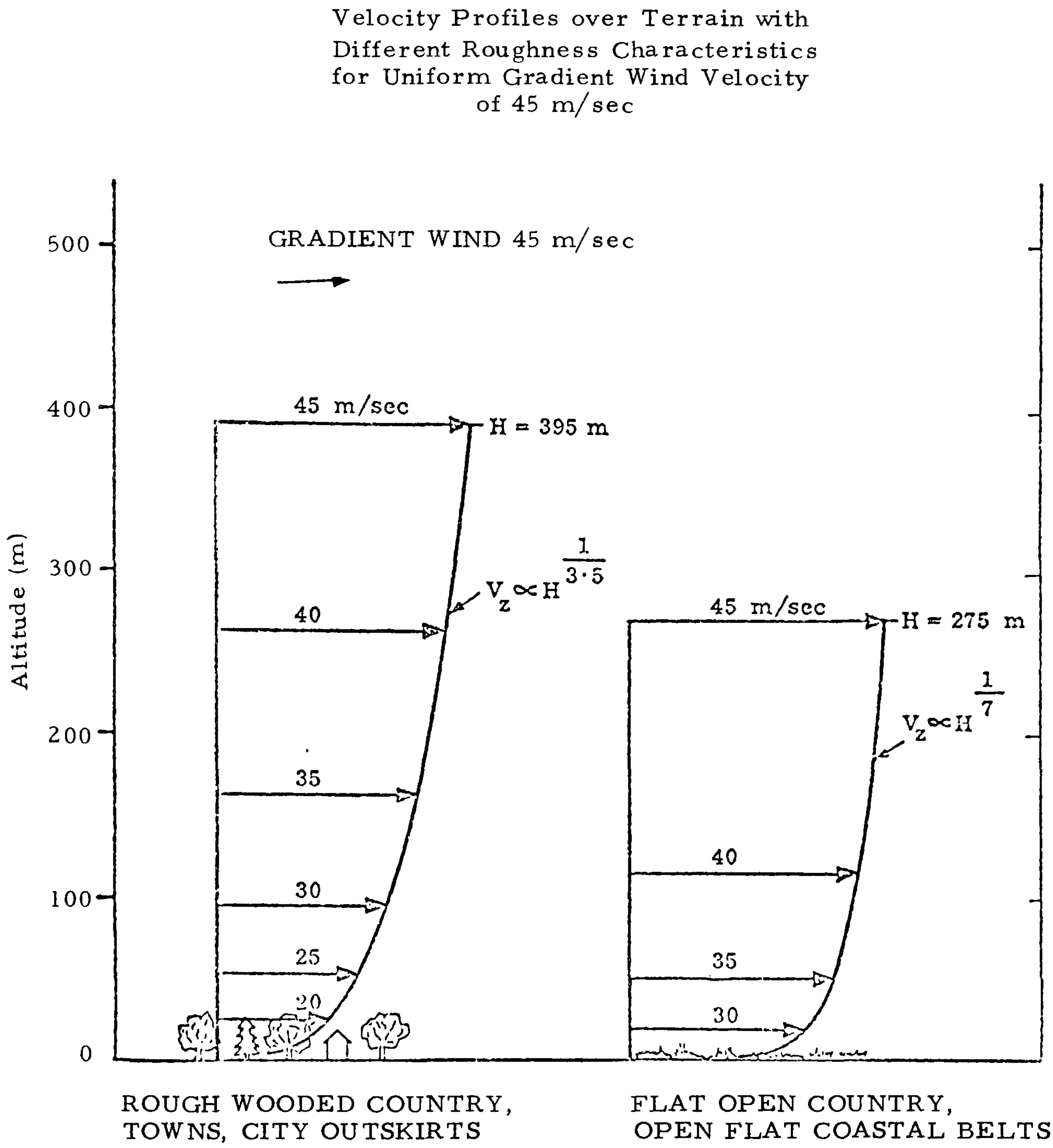


Figure 14. Effect of roughness on boundary layer velocity (Ref. 23).

- Changed evapotranspiration leads to changes in cloud cover.
- "Potential temperature" is higher over natural than urban areas.

These observations suggest that large scale surface alterations associated with installation of solar photovoltaic receiver or heliostat fields need to be examined by meteorologists. He suggested that one might expect some effect in altered thunderstorm precipitation systems.

Auer suggested however that land use occasioned meteorological anomalies in the Southwest would probably not be as severe as in the Mid-west or Northern plateau areas, for example. This is because, in the Southwest, there are fewer precipitation systems. The greatest land-use-related meteorological changes are associated with areas displaying the largest normal changes.

Auer concluded by noting a caution: that much of this is surmise. Nevertheless, like Cermak, he felt that this is possibly an area that merits examination.

We have been discussing alterations in local weather. One must not assume reflexively that these effects are necessarily adverse. From the multiple-use point of view, agriculturalists might find some small changes to be beneficial. We have already noted the suggestion that shaded areas beneath panels might be put to constructive use. Several writers, including the authors of the LMFBR E.I.S. (Ref. 9) suggested that increased surface roughness would have a beneficial effect in reducing surface wind erosion.

Severe hailstorms, in "hail alley" particularly (Colorado-Nebraska border vicinity), cause $600 million agricultural damage and $150 million property damage annually (Ref. 48). This damage is severe — and worse, it is concentrated (Ref. 49), so that the economic impact of a specific storm strikes with extraordinary severity within one county, or even one section. This has two implications for solar development.

First, the areas struck by most of these hailstorms are not now high technology areas containing great capital value per unit area. What would be the economic and generating capacity loss if such an onslaught chanced to strike a photovoltaic generating station?

Second, to what extent could the frequency of such episodes be modified inadvertently by changes in heat balance, humidity or boundary layer velocities?

Noise Pollution — All Technologies: Photovoltaic generating stations will be quiet. Presumably there will be the usual 60 cycle hum associated with transmission lines.

Flat plate solar collectors will probably require pumps or blowers to circulate heat exchange fluids. This equipment, even though situated at the load center, need be no more annoying than the sounds of forced draft heating and air conditioning equipment. Further, it will not necessarily be located in the circulating building air.

Concentrator steam electric systems will require some of the same rotating equipment used in conventional installations. Thus, one may expect such a solar facility to be no quieter at the equipment than an oil fired turbine generating plant for example. However, sound levels at the perimeter fence may be very low. Further, solar installations are not expected to be sited in populated areas.

Radiation — All Technologies: No nuclear materials are associated with any terrestrial photovoltaic installation. No ionizing radiation of any sort can be expected to be emitted from solar facilities.

The geosynchronous satellite generating station however is quite a different matter. It is proposed to use nuclear tugs, for example. At earth launch, the nuclear materials would be cargo. However, the consequences of an aborted launch followed by burn-up and/or disintegration are staggering to contemplate. Most careful consideration must be given all design options and all abnormal event scenarios prior to any construction and operation commitment.

It is proposed to transmit generated power back to terrestrial receivers using microwave radiation at about 3×10^9 Hz. Entirely aside from "leakage" around the mainbeam, one must wonder about the consequences of incorrect attitudes. Would it be possible for transient difficulties in attitude correction to cause the main microwave beam to strike urban areas? And what would be the consequences to aircraft passengers intercepting the beam?

The physiological and ecological effects of microwave radiation are certainly not thoroughly understood. Enough is known, however, to suggest great caution (Refs. 7, 8 and 34).

It would be very surprising if there were no public concern over these potential problems (whether well founded or not). In fact, it seems quite possible that public reaction might become at least as vigorous as that surrounding nuclear plant siting.

Historical, Archaeological, and Paleontological Values: Very little can be said on these matters on an a priori basis, because they are completely site-specific. Because solar development will start slowly, and because of the light construction occasioned by most photovoltaic solar facilities, salvage archaeology and paleontology can perhaps precede and accompany construction. Many of the early Indian settlements of the Southwest (such as Canyon deChelly and Mesa Verde) were located in or near rough terrain unsuitable for solar station installations.

Accidents, Disasters and Sabotage: This subject appears to have two aspects: the inherent vulnerability of central station and grid dispersed installations, and the environmental consequences of damage:

- Vulnerability to Accident: We have already discussed hailstorms. Photovoltaic panels may be especially vulnerable to fracture by hail or airborne debris.

  It is possible that polycrystalline CdS panels could continue in operation after damage from impact. Single crystal Si panels may not survive. Although a catastrophic event effecting many panels is conceivable (e.g., hail), it is not likely.

  The authors of the Dow Process Heat Study (Ref. 50) have considered the reliability-vulnerability issue from the plant operations point of view. They suggest that panels "quite probably. . . could be maintained on a replacement basis with a malfunctioning unit removed and spare inserted." Near term capital costs of photovoltaic panels are likely to be so high as to preclude a large inventory. Heliostat pieces may be easier to stock.

- Vulnerability to Sabotage: Szego (Ref. 26) reports that InterTechnology Corporation has examined various vulnerability and low cost countermeasure scenarios. He states that qualified requestors may obtain further details from ITC.

  On an a priori basis we see that a large field of solar receiving panels might be vulnerable to terrorist attack. However, the diffuseness and modular construction preclude wide-spread or irreparable damage, at least in a photovoltaic facility.

  In this respect, a photovoltaic solar installation offers very favorable alternatives to nuclear, or even coal-fired plants. Further, a solar installation is more likely to enjoy widespread public acceptance.

  As Zeren (Ref. 14) indicated, the utility industry is aware of the increased vulnerability of grid dispersed stations, but feels the compensating advantages may outweigh the objections to grid dispersal (cf. "Siting and Grid Dispersal"). Simple acts of vandalism are more possible in such small stations, as well as in residential installations. Prince (Ref. 6) states this has not been a problem to date.

- Seismic Events: Although optimized orientation of photovoltaic panels is desirable, precise alignment is not absolutely essential for extraction of power at derated capacity. Light construction favors prompt repair of damaged supports. Modular construction permits portions of an installation to be out of service without scramming the entire plant. The greater part of a photovoltaic plant seems to be less easily damaged than a conventional plant.

Power conditioning, storage, and transmission peripherals would be about as vulnerable as equivalent facilities at conventional plants.

- Fire: There seems to be little prospect for a fire to begin, or to propagate. An important exception is in the case of hydrogen cycle energy storage. Modular construction reduces the impact of such an accident (Ref. 27).

- Environmental Consequences of Damage: In a photovoltaic installation, the airborne distribution of CdS or GaAs and its introduction into surface waters appear to be the only non-local environmental effects of the damage scenarios we have addressed above.

  With respect to surface water contamination — it appears to be a trivial engineering problem to design panels to preclude this in the case of simple fracture. Normally CdS panels would be hermetically sealed. If the transparent seal were fractured, erosion would be possible. By judicious design, perhaps at some loss in efficiency, erosion products could be captured within the panel behind the remaining panel seal.

  In the case of extensive damage such as could be caused by a tornado, for example, rapidly mounted emergency procedures to collect and secure damaged panels would be required.

Geosynchronous Satellite Generating Station — Environmental Problems

Propellant Combustion: One concept of a satellite power station was depicted in Figure 5. Other conceptual studies are to be performed under two 18-month NASA contracts recently announced (Ref. 56) to be in final negotation with Grumman Aerospace Corp., Bethpage, N. Y., and McDonnell Douglas Astronautics, Huntington Beach, Calif. NASA's Marshall Space Flight Center, Huntsville, Ala., and Johnson Space Center, Houston, Texas, are committed to space station projects which are to incorporate solar generating stations.

These stations are to be located at 22,300 mi altitude and house crews of about 200. Typical concepts involve construction of solar power satellites by these space station crews. Satellite solar panel "fields" are currently believed to require structures 20 to 50 mi^2 in area, and perhaps 600 ft in depth. One concept envisions use of discarded fuel tanks as structural elements. Target date for design decision is now in 1978.

Current plans require lifting of crews and very large quantities of materials into orbit using the space shuttle launch vehicle (SSLV). Williams (Ref. 34 and Table 6) projects 1805 SSLV launches per year in the period 1995-1999.

Each SSLV launch requires combustion of 1,234,000 lb of liquid fuel (H_2 + O_2) producing approximately that quantity of water vapor, and potentially vast quantities of NO_x due to reactions in entrained air.

In addition, each SSLV launch requires combustion of about 2.2×10^6 lb of solid fuel (Ref. 57). A typical solid fuel composition is given in Table 9 (Ref. 58). Production and disappearance rates of fuel combustion products are calculable as functions of altitude. Table 10 displays the principal constituents of the "inviscid core" of a mature exhaust plume corresponding to the fuel composition of Table 9.

It is important to realize that this simulation is for a mature plume calculated without regard to entrainment and reaction of ambient air. "Staging" occurs at 140,000 ft. Prior to this, a variety of transient free radical and stable species have been produced and destroyed at plume temperatures $\leq$ 2700 K. Entrained air can react with or transport some of these. Species present (and mole fractions) at 2690 K and 8.2 atmosphere were calculated to be (Ref. 58):

$A\ell C\ell$ (.0037), $A\ell C\ell_2$ (.0023), $A\ell C\ell_3$ (.0005)
$A\ell OC\ell$ (.0019), $A\ell OH$ (.0003), $A\ell O_2H$ (.0005)
CO (.252), CO_2 (.021), $C\ell$ (.0038), $FeC\ell_2$ (.0013)
H (.010), $HC\ell$ (.154), H_2 (.293), H_2O (.163),
N_2 (.091), OH (.0015), and minor products

About 99% of the air in the exhaust plume is entrained air, indicating that the effect of reactions with air cannot be ignored. Predictive modeling now indicates that two-phase flow, afterburning, and radiative energy transfer combine to increase the calculated heat content of the plume more than three-fold over pre-1973 estimates. Consequently most cloud-plume and dispersion calculations previously reported are invalid. Plume rise is very much greater than formerly supposed. Ground-level $HC\ell$ concentrations are therefore lower, but very much more $HC\ell$ is injected directly into the upper troposphere (Ref. 57).

Particulate matter is created directly in solid propellant combustion. It is possible also that free radical reactions can lead to formation of additional condensible organics. One must ask if condensation nuclei are being created. This concern must be related to the formation of enormous quantities of water vapor. Will precipitation result? Would precipitation wash out much of the particulate burden, $HC\ell$, and $A\ell C\ell_3$? If so, would this reduce air pollutant levels at the expense of local acid rainfall injury? Will triboelectric charge generation have detectable chemical and meteorological effects? Meteorological and cloud physics predictive modeling are being pursued at Marshall Space Flight Center (Ref. 57) in an attempt to answer

TABLE 9. TYPICAL SOLID FUEL COMPOSITION FOR SPACE SHUTTLE LAUNCH VEHICLE (REF. 58)

%	Material	Composition
16.0	Reducing agent	Metallic $A\ell$
69.6	Oxidizer	$NH_4\, C\ell O_4$
12.0	Binder	$C_{6.9}\, H_{10.1}\, O_{0.3}\, N_{0.3}$ (equiv. formula)
0.4	Binder	Fe_2O_3
2.0	Stabilizer	$C_{6.2}\, H_{7.0}\, O_{1.2}\, N_{0.03}$ (equiv. formula)

TABLE 10. CALCULATED COMPOSITION OF THE INVISCID CORE OF A TYPICAL SSLV EXHAUST PLUME (Fuel Composition, Table 9, $p = 8 \times 10^{-4}$, atmos, T = 471 K)(Ref. 58)

Constituent	Mole Fraction x 10^3	Constituent	Mole Fraction x 10^3
H_2	470	$A\ell C\ell_3$	9.6
CO_2	200	C_2H_4	6.6
$HC\ell$	150	H_2O	5.7
N_2	94	NH_3	0.05
CO	67	$FeC\ell_2$	0.01

such questions. Atmospheric monitoring of cloud plumes from Titan launches is being performed by a large group from Langley Research Center. Johnson Space Center personnel are responsible for ecological aspects of SSLV launch studies.

The present state of the art is that predictive modeling results and monitoring of plume behavior are now converging. It is becoming possible to make conservative overestimates of exhaust plume effluents and ground-level concentrations. Other areas of environmental concern (e.g., cloud physics) are proving less tractable (Ref. 57).

Other contractors involved in dispersion, windfield, cloud physics, or other environmental problem areas include System Analysis, Inc., Lawrence Livermore Laboratory, Brookhaven National Laboratory and University of Pennsylvania. EPA may find it desirable to maintain close liaison with the NASA facilities performing and directing plume composition and dispersion studies, etc.

Nuclear Materials: It is proposed to launch nuclear cargoes for subsequent fueling of nuclear propelled space tugs (Ref. 34). This idea should be viewed with great wariness.

The consequences of a launch abort followed by atmospheric burnup and/or disintegration are staggering to contemplate. Injection of nuclear material into the earth's atmosphere or its distribution onto the ground and into surface waters must be prevented. Perhaps it is possible to design an absolutely impregnable containment which would not preclude subsequent entry by space station crews. EPA may wish to maintain close liaison with appropriate ERDA and NASA offices.

Microwave Radiation: Power generated in the proposed photovoltaic panels is to be converted to 3.3 gH_z microwave radiation and beamed to earth receiving and rectifying antennas ("rectennas"). Williams (Ref. 34) writes of beam intensities of 500 to 1000 W/m^2 at the center of rectennas, 10 to 100 W/m^2 at the edges, and an overall transmitting-receiving efficiency of 68%. He suggests control by phase-locking transmitter elements onto a pilot signal originating in the rectenna center. One purpose of this proposed arrangement is to preclude satellite attitude errors causing inadvertent high intensity microwave irradiation of populated areas. He believes security fences would adequately restrict the general public to areas receiving less than 1 W/m^2. (1% of U.S. standards and about 10% of Eastern European standards.) Further, he suggests that microwave intensities under the rectennas would be less than 10 W/m^2, low enough to permit industrial siting.

Microwave radiation is non-ionizing; its most apparent effect on tissue is heating. Whole body 3.3 gH_z irradiation at 100 W/m^2 would dissipate no more than 57.5 W in a human target, an amount said to be easily dissipated. For perspective: the basal metabolic rate of a resting human is 70 to 90 W, and about 290 W during moderate work. The U.S. standard of 100 W/m^2 for human whole body microwave irradiation is derived from these figures (Ref. 59).

"Microthermal" effects are nonuniform heating due to nonuniform tissue absorption. Some studies suggest adverse microthermal effects may occur below 100 W/m^2. Soviet researchers think abnormal nonthermal effects occur also (Ref. 60); the USSR standard is therefore 0.1 W/m. This is 1000 times more stringent than the U.S. standard.

It seems that great care must be exercised in developing specifications for microwave power transmission target accuracy and securing safe zones around rectennas. Regardless of whether or not somatic or genetic damage could occur at 100 W/m^2 irradiation, most humans would probably react with anxiety to an unseen source of body heat approximating 70% of their basal metabolic rate. The effects on aircraft passengers and birds need careful assessment.

In addition, effects on radio transmission and the possibilty of inadvertent potentials induced in materials (e.g., blasting cap leads) need to be assessed.

For a more thorough review of these points and others, Williams' paper (Ref. 34) and Dickson's (Ref. 7) and their bibliographies should be consulted.

Noise: The terrestrial receiving array should be quiet, except perhaps for 60 cycle hum in peripheral equipment such as transmission lines. The many SSLV launches (several per day cf. Table 6) may each approximate the noise generated by a Saturn V launch (Ref. 34). It seems unlikely that these launch noises would be perceived forever by all residents near the Kennedy Space Center as being desirable attractions. Landing shuttle orbiters would create sonic booms. Perhaps resiting the program to a remote location might be environmentally desirable. It is beyond the scope of this report to analyze the economic viability of resiting.

Materials and Energy Requirements: Because designs are still conceptual and changing, it is impossible to make precise materials and energy estimates. Glaser (Ref. 61) stated that the energy required to fabricate, launch and construct the satellite would correspond to this schedule:

Materials	Months of Operation to Pay Out
Propellants	6
Solar Cells	3
Ground Support Facilities	3

Williams (Ref. 34) believes two years to be realistic. Dickson (Ref. 7) calculates that Glaser's design would require 10^5 kg of Ga in GaAs cells — four times more Ga than the U.S. Geological Survey anticipates will be the cumulative total production by year 2000. Williams, loc cit, has correctly pointed out that structural material requirements should be very much lower than for terrestrial applications.

Attention to materials demands is essential, and may profoundly influence design features. Commitment of a large fraction of GaAs production capacity to geosynchronous satellite power stations would preclude its use in large terrestrial solar applications.

Hydrogen Cycle Storage — Direct Effects

The hydrogen cycle (water electrolysis cell-hydrogen/air fuel cell) is a particularly good match to solar electric generation because it requires dc power, uses modular construction, and therefore can more rapidly track load projections with shorter lead time and is applicable to grid dispersed facilities. It is much more efficient than oil fired turbines, is not site specific, is quiet and clean and does not consume significant quantities of water (makeup water requirements are 5% or less) (Ref. 27).

Principal components of a hydrogen cycle system are electrolysis cells, hydrogen storage equipment, fuel cells, power conditioning and handling equipment, and other peripherals. In some systems the fuel cells and electrolysis cells can be the same units. Power conditioning equipment possibly may be common to the generating station. Hydrogen storage methods include storage as $FeTiH_2$ (Ref. 51) using low grade heat for degassing. A detailed unit operations oriented environmental assessment of a 500 MW fuel cell peak shaving plant was performed by Sears (Ref. 27). Figure 15 is a flow diagram for the plant, and Table 11 summarizes the environmental releases. A significant problem is release of asbestos in electrolysis cell off-gas and cell flush waters. Recent progress in development of solid polymer electrolyte/separators may obviate the problem. Release of pyrolysis products of SPE (typically fluorosulfonated polymers) in the event of a cell fire needs to be evaluated.

Alternative Subsystems

Steam Reforming: Complete reliance on electrolysis for H_2 production may be impossible, because peak shaving may be required in excess of off-peak solar generating capacity. Optimum utilization of existing facilities suggests steam reforming of distillate oil and oxidation of hydrogen in the fuel cells. Steam reforming is the only applicable, well developed alternative to electrolysis. Design, performance and atmospheric emissions are described by Lueckel and Farris (Ref. 52). Based on performance of a 26 MW_e plant, emissions are:

Pollutant	lb/10^6 Btu Input
NO_x	0.020
SO_2	3×10^{-5}
Particulates	3×10^{-6}
Smoke	Nil
Noise	Suitable for Residential Area

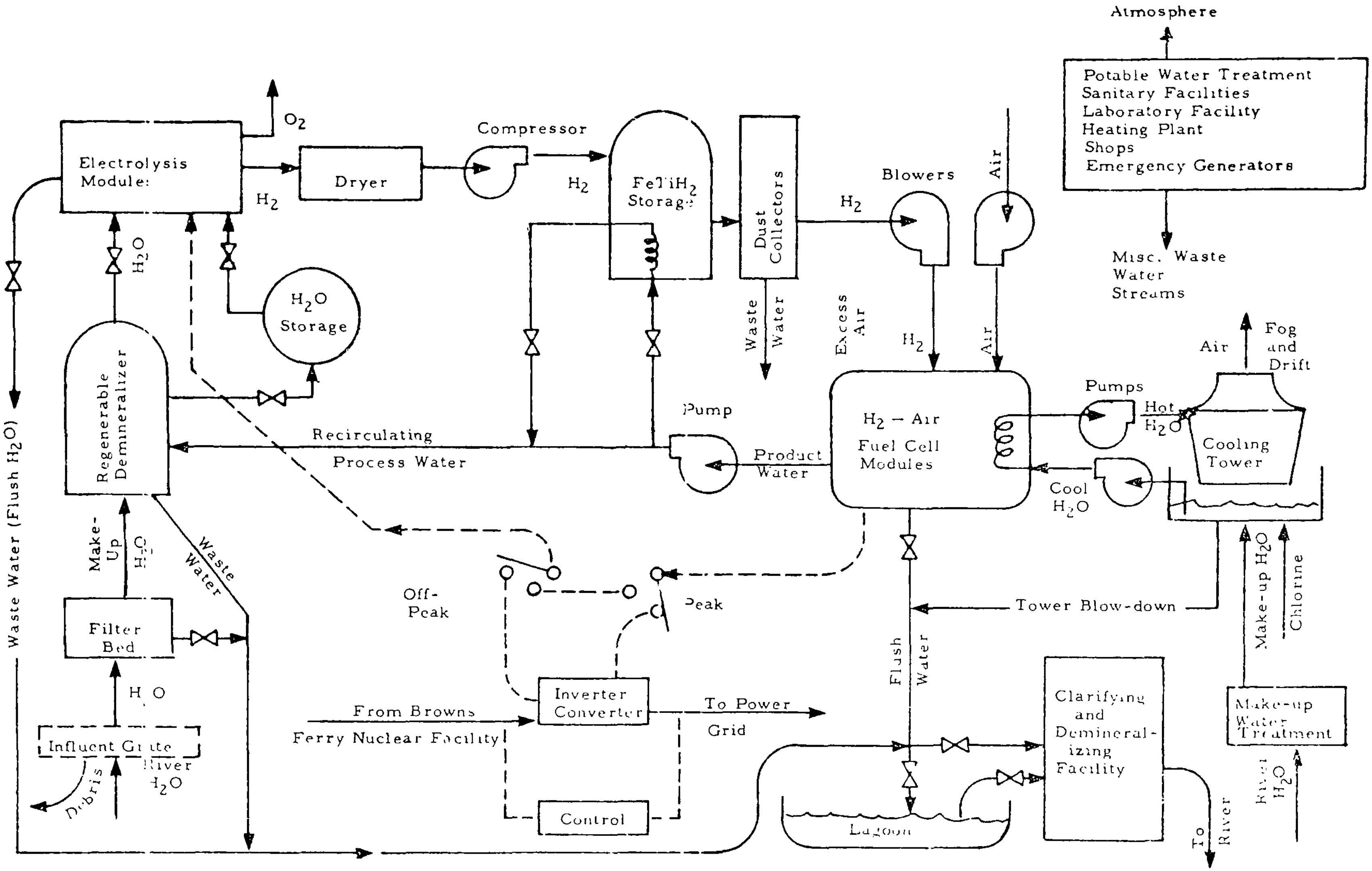


Figure 15. Unit operations detail for an electrolysis – fuel cell hydrogen cycle (Ref. 27).

TABLE 11. SIGNIFICANT ANTICIPATED DIRECT ENVIRONMENTAL RELEASES FROM A 500 MW ELECTROLYSIS-FUEL CELL HYDROGEN CYCLE FACILITY (REF. 27)

Component	Atmospheric Emissions	Waste Water Discharges	Solid Waste	Accident or Malfunction
Process Water Treatment Facility	None.	Filter Bed Backflush (to River). Demineralizer Regeneration (to Lagoon).	Occasional discard of spoiled resin (to landfill).	Malodorous Emissions from Anaerobic Processes in Filter Bed
Electroysis Units	Option (a): Asbestos Option (b): Deteriorated SPE Entrained in 65,600 Scfm O_2.	Option (a): Asbestos in flush (to Lagoon). Option (b): Deteriorated SPE in Flush (to Lagoon)	Sludge (Cf. Waste Water).	Pyrolysis Products of SPE
Hydrogen Storage	None.	None.	Discard of Spoiled Fill (to oxide conversion or recycle facilities).	FeTi and $FeTiH_2$ Granular and Powdered Material (to work place).
Fuel Cells	**Excess Air**	Option (a): Asbestos in Product Water and Flush. Option (b): Deteriorated SPE in Product Water and Flush.	Sludge (Cf. Waste Water)	Pyrolysis Products of SPE.
Cooling Towers	Fog and Icing. Drift (containing Treatment Chemicals). Heat. Noise.	Treatment Chemicals in Blowdown (to Lagoon).	Sludge (Cf. Waste Water).	Wood Smoke and Pyrolysis Products if Timber Construction Used. PVC Pyrolysis Products
Power Handling Section	Traces PCBs (SF_6?) from Transformers. Herbicides from Rights-of Way. Smoke from Slash Burning.	None.	None.	PCB's in Explosion (SF_6).
Sanitary Facility	None.	Pathogens, BOD, Treatment Chemicals	Sludge	Raw Sewage

Cryogenic Storage of Oxygen and H_2

Both technologies are very well developed due to NASA R&D. They require energy expenditure to perform liquefaction and maintain vacuum. Liquid hydrogen is much less safe to store and handle than $FeTiH_2$.

H_2 — oxygen fuel cells, using alkaline electrolyte, are better developed than H_2 — air fuel cells, which must use acid electrolyte (Ref. 53). Periodic flushing of the fuel cells will require different waste treatment strategies in the two cases.

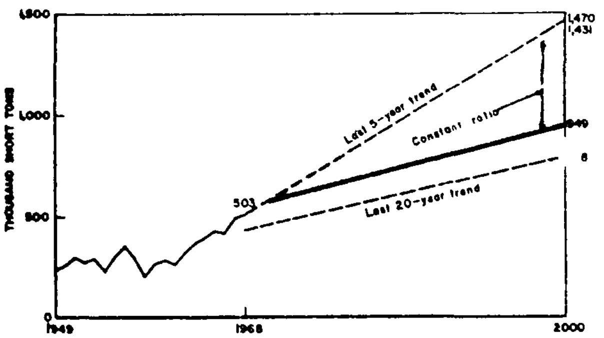
Hydrogen as a Fuel

Another proposal (Refs. 28, 54, 55, for example) is to produce hydrogen by electrolysis, but to transport it to demand centers as pipeline gas and combust it on site in conventional gas fired applications. No fuel cells would be required, but pipeline transmission corridors would be required. Inevitably, safety considerations would need detailed study. Hydrogen combustion (pure or CH_4-blend) should be particularly clean, but NO_x emissions would require evaluation for specific burner designs.

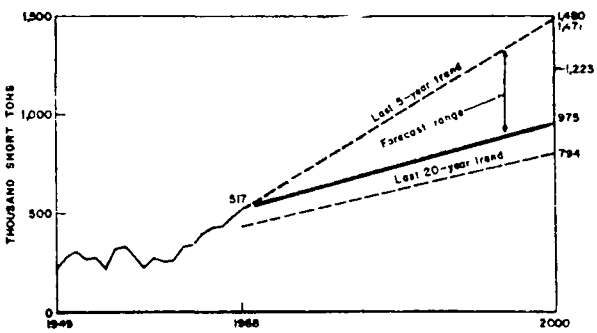
Resource Commitment and Depletion

Silicon: Total domestic and world reserves are huge. Published data (Ref. 62) suggest that several hundred million tons of 95% SiO_2 are available domestically. Known reserves of 98% SiO_2 are sufficient to support 10^8 tons (9.1×10^{10} kg) Si production. Few states have published survey data; therefore, the true reserves exceed the known reserves by an uncertain, but certainly large margin. Figure 16 (Ref. 62) presents production and demand projections without regard to major solar power applications. Domestic production is only one-third of world production.

All silica mining, incidentially, is open-pit, with a small over-burden to ore ratio.



Comparison of Trend Projections and Forecasts for Primary Silicon Production.



Comparison of Trend Projections and Forecasts for Silicon Demand.

Figure 16. U.S. silicon production and demand projections, without regard for major solar power applications (Ref. 62).

Current Si solar cell production is a small fraction of total Si use. In 1975, for the first time, terrestrial applications exceeded space applications (1000 m^2 versus 500 m^2) (Ref. 17). Assume 40 W/m^2 capacity, (24 hr average in favorable sites), and 175 μm thickness. This is intermediate between the 250 μm current devices and Prince's goal of 100 μm devices (Ref. 6). A 1 GW_e facility would require 25 x 10^6 m^2 of panel with a volume of 4375 m^3. This is 10.2 x 10^6 kg or 11,300 short tons.

> Conclusion: 50 GW_e silicon photovoltaic capacity in the U.S. in year 2000 would increase forecast demand 38 to 58% but would have minor impact on domestic reserves.

Cadmium: This element is fairly rare, although it sees numerous industrial applications. Figure 17 depicts supply/demand relationships for Cd which must be considered in any massive solar power development using CdS. The U.S. already uses about one-half of world production.

Cadmium is almost wholly a byproduct of zinc production. Its availability is tied to zinc demand, because it does not produce sufficient income for zinc producers to adjust production schedules to meet Cd demand.

Apparent recoverable domestic cadmium reserves are estimated to be 8.6 x 10^7 kg. World reserves including U.S. are estimated to be 6.4 x 10^8 kg. Recent discoveries in middle Tennessee may increase domestic reserves by only 5 to 15% (Ref. 62). About 25% of our cadmium is imported (Ref. 63). Demand-production trends are given in Figure 18.

Using Project Independence numbers (Ref. 23), viz 5.0 x 10^6 kg Cd/GW_e, we find that the estimated total recoverable domestic cadmium reserves correspond to only 17 GW_e of generating capacity. Actually, the Project Independence numbers were derived from 20 μm CdS in CdS/Cu_2S panels, with an assumed efficiency of 7%. Substantial reductions in film thickness and perhaps a small improvement in efficiency can be anticipated. Nevertheless, CdS appears to be resource limited.

The situation may be more serious than for gallium, because unlike the latter, cadmium sees widespread industrial application. Commitment of cadmium to solar development may be expected to force other users to seek substitutes which may be environmentally less desirable. An exception is electroplating. There is already a tendency to substitute zinc for cadmium.

The cadmium supply/demand situations created by solar power development therefore seems to merit attention by EPA, ERDA and various U.S. mineral resource agencies.

Gallium (Refs. 62, 64, 65): Although gallium is relatively abundant, there do not appear to be any deposits of gallium ore rich enough to justify processing for gallium alone. The apparent exceptions are germanite which may contain 1% Ga, and gallite, $CuGaS_2$ found in South Africa. However they are too rare to be counted as resources. Many coals which contain

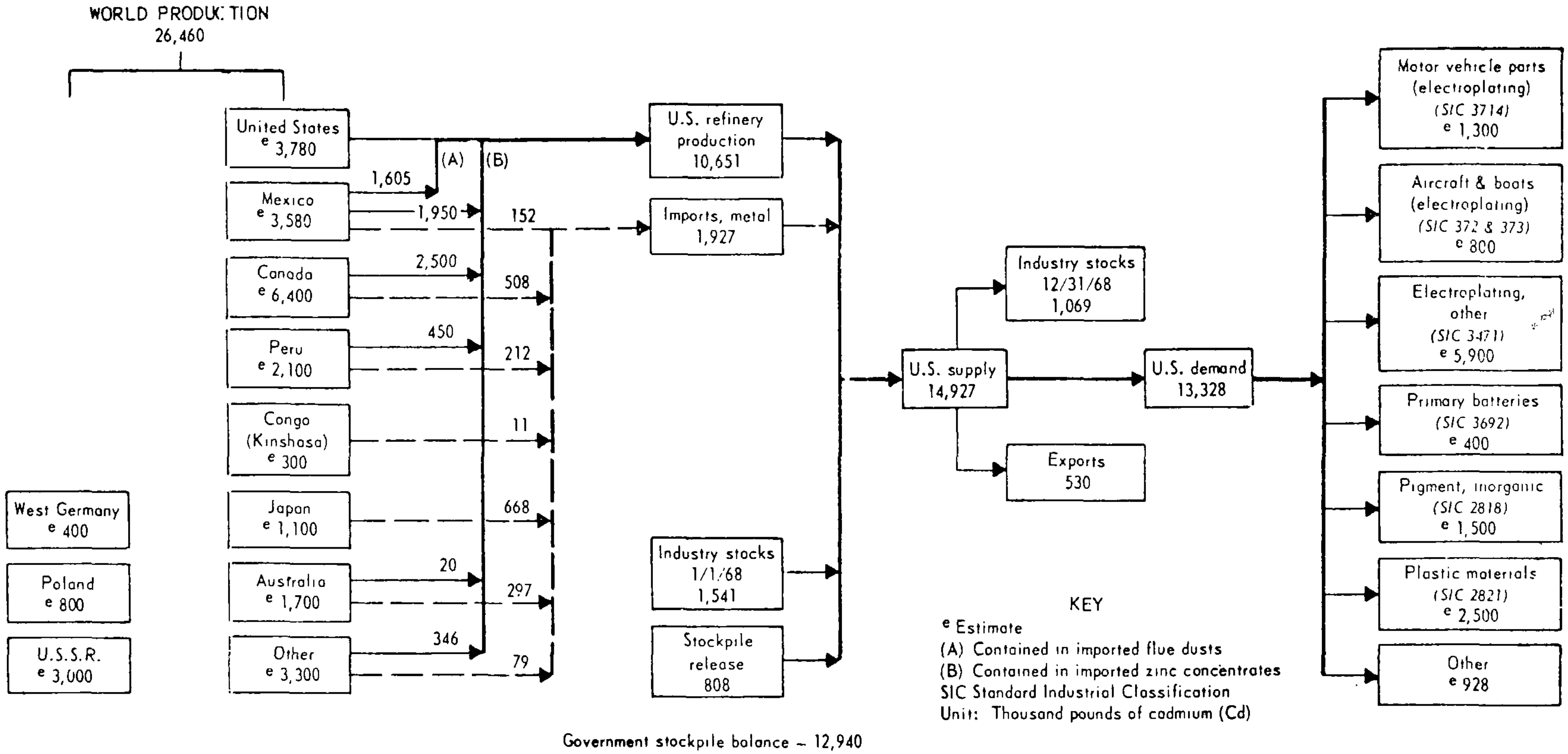


Figure 17. 1968 supply-demand relationships for cadmium (Ref. 62) (units in 1000 lb or 454 kg).

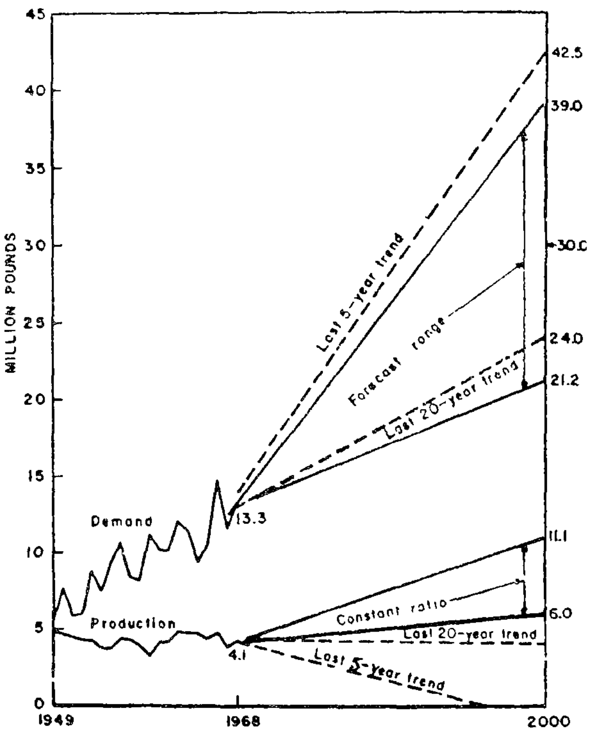


Figure 18. Comparison of U.S. trend projections and forecasts for primary cadmium (Ref. 62).

germanium also contain gallium. Fly ashes of these coals occasionally contain as much as 0.1% Ga. This cannot be considered a dependable resource upon which to base a solar power industry. Basically, gallium is a by-product of aluminum and zinc refining.

Uncertain data suggest domestic reserves are 2×10^6 kg in bauxite, and 0.7×10^6 kg in zinc blende (Ref. 62). About 96% of our bauxite is imported, however (Ref. 63). Gallium supply problems may encourage some recycling of retired GaAs devices, reducing long term (but not short term) demand as well as reducing environmental releases of Ga and As. Figure 19 presents production and demand forecasts for Ga without regard to major solar developments.

Assuming 1 μm thick GaAs (Ref. 7) generating about 20 W/m^2, a 1 GW$_e$ plant requires 50×10^6 m^2, 50 m^3, 2.67×10^5 kg*, or 294 short tons. This corresponds to 141 short tons of Ga (1.28×10^5 kg), about ten times cumulative domestic production 1975-2000, assuming 500 kg/yr.

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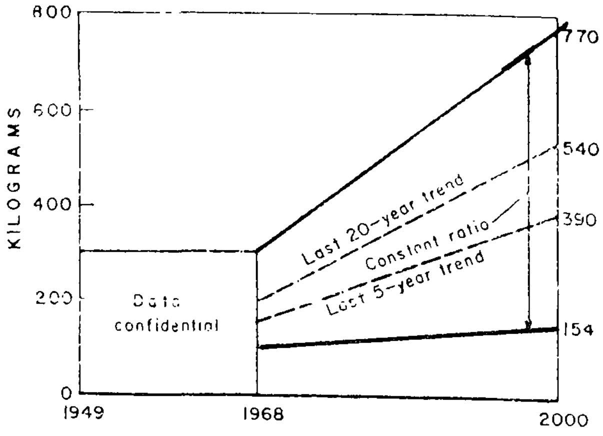
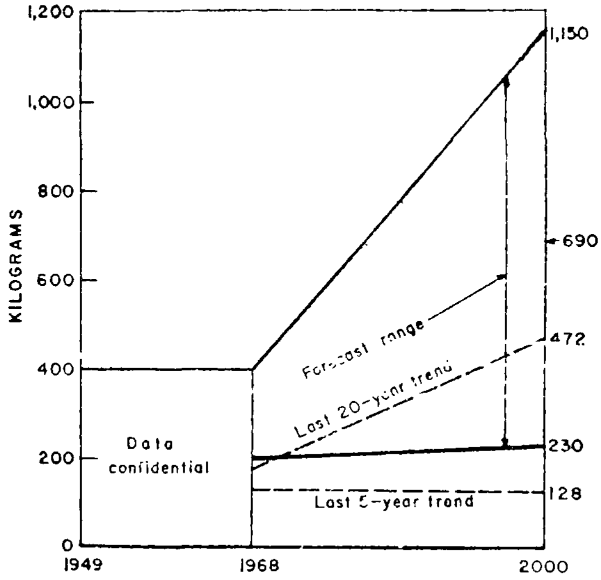
*Using density calculated from crystal structure assuming cubic cell, $a_o = 5.646$, $Z = 4$ (Ref. 66).



Comparison of Trend Projections and Forecasts for Primary Gallium Production.



Comparison of Trend Projections and Forecasts for Primary Gallium Demand.

Figure 19. U.S. gallium production and demand projections, without regard for major solar power applications (Ref. 62).

If U.S. reserves are indeed only 2.7×10^6 kg, the requirements of one 1 GW_e plant would represent nearly 5% of our domestic reserves. World reserves are estimated at 110×10^6 kg (Ref. 64).

The Project Independence data (Ref. 23) create an even bleaker picture. They assume 1.4×10^6 kg/GW_e — about 112 times cumulative domestic production of 500 kg/yr 1975-2000. Our experience with dependence on foreign oil suggests ERDA may wish to monitor GaAs utilization and supplies with some care.

Recently Varian announced development of GaAs capable of withstanding the higher temperatures needed in concentrators. Should this development prove to be practicable in large facilities, GaAs photovoltaic applications would cease to be resource limited.

Arsenic: The U.S. does not seem to face resource limitations with this element. U.S. domestic reserves are said to be 1.7×10^9 kg and world reserves 3.8×10^9 kg (Ref. 62). A 1 GW_e, 1 μm GaAs facility would require 1.4×10^5 kg or 152 short tons. That represents about 50 years' domestic production at current levels (Figure 20) and about six times current domestic annual demands but only 0.008% of U.S. reserves. GaAs applications will be limited by Ga availability, not As.

Miscellaneous Candidate Photovoltaic Materials: From time to time other materials are suggested and some of these may achieve substantial

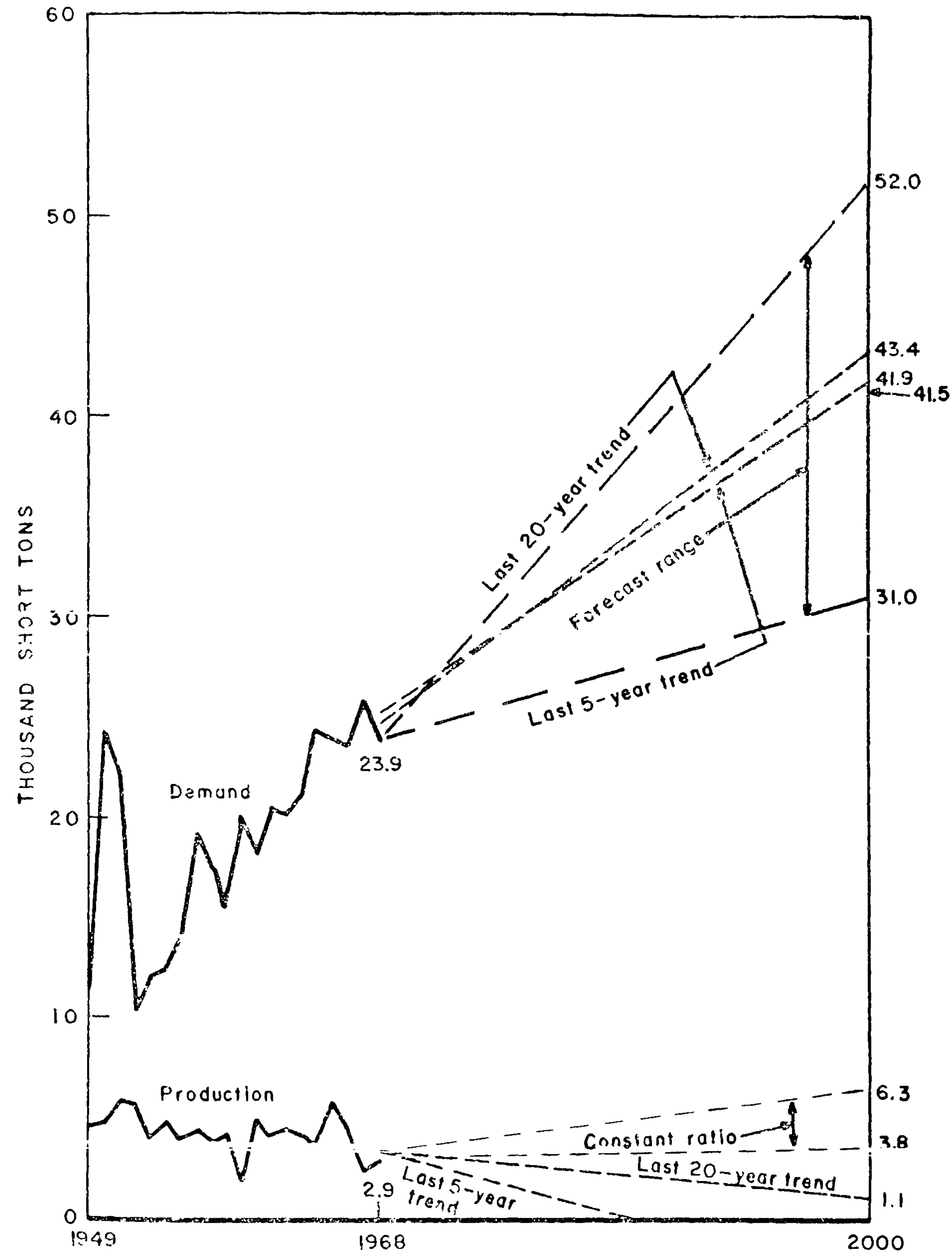


Figure 20. U.S. arsenic demand and production trends, disregarding solar development (Ref. 62).

use. For this reason, we supply Table 12 which presents some data needed to judge resource commitment. We include GaAs, CdS and Si for comparison.

This table does not show how much of the indicated reserves are committed by other uses at current or foreseen application rates. In some cases, current uses exceed known reserves as in the case of copper. It does not indicate improvements in reserves possibly developed by improved byproduct recovery methods, new mineral explorations, etc. Most importantly, some of these reserve data are based on current price structures. If prices increase dramatically, former "nonrecoverables" in low grade ores or base metals will suddenly become "reserves," as happened to mercury in the 1960s.

Entirely new supplies of trace metals, and even sulfur, can develop from pollution control technology. Sulfur from fuel and flue gas desulfurization, gallium from flyash, and selenium and tellurium from smelter waste stream recovery are examples. Detailed discussion of these subjects is entirely outside the scope of this report. Nevertheless, these matters may assume overwhelming importance and appropriate offices of EPA, ERDA and the Department of the Interior, for example, may wish to keep each other informed.

Glass and Aluminum: Current and anticipated technology require hermetic seals on the front surface of thin film (CdS and GaAs) photovoltaic panels. Research is underway to develop CdS panels with the semiconductor sprayed directly onto float glass. In any event, some sort of long-lived rear support surface will be required, which may be the conductor.

Suppose each photovoltaic panel requires a 3/32 inch glass front surface and an 1/8 inch aluminum back surface. Assuming 50×10^6 m^2/GW_e (538×10^6 ft^2/GW_e) we need for each GW_e capacity:

4000×10^6 kg (4.4×10^6 tons) glass

5100×10^6 kg (5.6×10^6 tons) aluminum

This aluminum requirement will be in addition to any used in support structures, transmission towers, and transmission lines.

Lead: This element would find potential application in storage devices. Although lead would probably be unsatisfactory in the long term (cf. the previous discussion) it will possibly see application in the earlier pilot and demonstration plants. We recommend that a review of technology and resource demands of lead-acid storage cells of utility size be performed. Extrapolation of lead requirements from automotive and electric powered vehicle use is likely to be an invalid exercise.

Domestic and world reserves of lead are believed to be 3.2×10^{10} and 5.4×10^{10} kg (35.3×10^6 and 60×10^6 short tons), respectively (Ref. 62).

Lithium (Refs. 62, 67): Experimental Li, Aℓ-iron sulfide cells have been demonstrated with a storage capacity of 150 W-hr/kg (compared to

TABLE 12. SUMMARY OF SOME PHOTOVOLTAIC MATERIALS DATA

Material	Density g/cm^2	Mol. Wt.	Element	Mass Element in 1 m^2 Panel 1 μ Thick, g	Assumed Thickness, μ in Application	Mass Needed in 1 GW_e Plant, 10^6	Reserves (Ref. 62) 10^6 kg U.S.	World
Si	2.33	28.09	Si	2.33	175	25	Unlim.	Unlim.
CdS	4.82	144.46	Cd	3.76	20 (Ref. 23)	5	86	635
			S	1.06		N/A	3×10^5	2×10^6
Cu_2S	5.6	159.14	Cu	4.5	1 (Ref. 23)	0.14 (Ref. 23)	77,100	Unk.
			S	1.1		N/A	3×10^5	2×10^6
GaAs	5.34*	144.64	Ga	2.56	1 (Ref. 7)	0.27	2.7	110
			As	2.78		0.14	1723	3810
CdTe	6.20	240.00	Cd	2.91	1 (Ref. 23)	2.4 (Ref. 23)	86	635
			Te	3.29		0.7 (Ref. 23)	7**	63**
$CuInSe_2$	5.7	336.28	Cu	1.1	Unk.	Unk.	77,100	Unk.
			In	1.9		Unk.	0.4	2.3
			Se	2.7		Unk.	23	108
InP	4.79+	145.79	In	3.78	Unk.	Unk.	0.4	2.3
			P	1.01		Unk.	Adeq.	Unk.

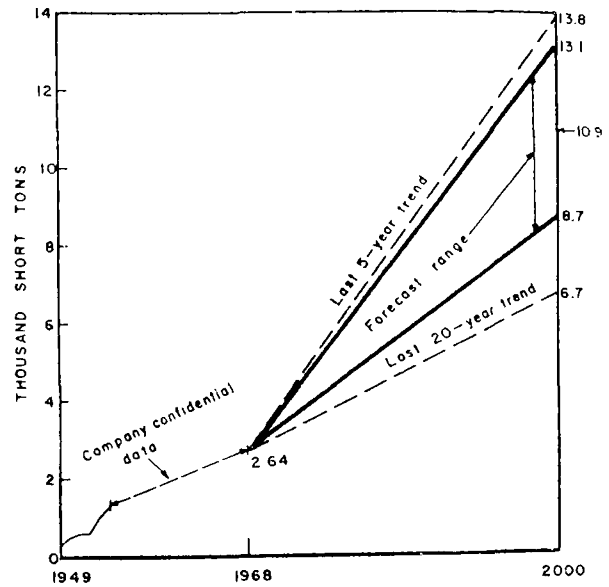
*Calculated from crystal structures using a_o = 5.646A, Z = 4 (Ref. 66).

**Improved byproduct recovery practices could increase this (theoretical limit $\leq$ 2x).

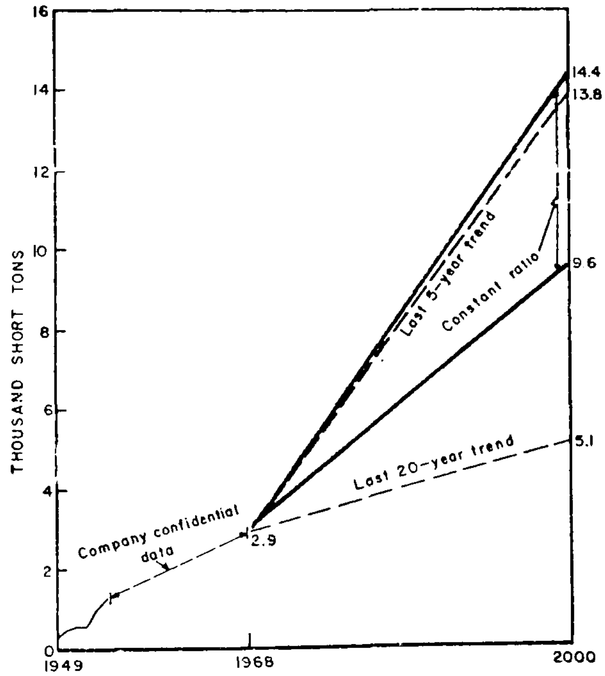
+Calculated from crystal structure using a_o = 5.869A, Z = 4 (Ref. 66).

25 W-hr/kg for lead-acid batteries). Thus, Li based batteries show unusual promise as light, high energy density storage components for electric vehicles and utility applications. Demand projected to year 2000 for these two applications is 2.7×10^8 kg and 5.4×10^8 kg of lithium, respectively. Additionally, fusion power reactors using lithium as fuel source, blanket and/or coolant may need an estimated 100 to 1000 kg Li/MW_e capacity. These uses of lithium may not materialize. Alternative battery materials (e.g., sodium) may be employed instead, and fusion may not work.

Production of this metal during 1974 was 3.4×10^6 kg domestically and 1.6×10^6 kg in the remainder of the world. Past and projected demand and production are displayed in Figure 21 in which fusion power and electric storage applications are disregarded. Production for 1974 fits almost exactly onto the 20 year trend line, rather than into the constant-ratio forecast region.



Comparison of Trend Projections and Forecasts for Lithium Demand.



Comparison of Trend Projections and Forecasts for Lithium Production.

Figure 21. U.S. lithium demand and production projections disregarding solar and fusion power application (Ref. 62).

New discoveries of lithium reserves and expanded exploitation of lower grade deposits make the reserve figures of Ref. 62 rather meaningless now. At a January 1976 Conference on U.S. Lithium Resources and Requirements, rather disparate points of view were expressed on the adequacy of lithium for the new storage and fusion applications (Ref. 67). Vine of USGS thinks domestic reserves are less than 10^9 kg, barely more than the projected storage battery requirements. Kunaoz of Foote Mineral Company thinks ore reserves are sufficiently large — and elastic — to satisfy conventional and new energy needs.

There is no concern about reserves being able to support conventional applications: the Kings Mountain area of North Carolina has at least a 100-year supply.

In assessing indirect effects of resource commitment, one must consider whether dedication of a major share of reserves or productive capacity will force other users to exploit alternative materials much less desirable environmentally. Clearly this can be an open-ended question, and to perform such a study is beyond the scope of this report. It needs to be done, however.

In the particular example of lithium, we could face an even more disastrous indirect effect. For if fusion power is developed successfully, we may have to dedicate much of the world's recoverable lithium to energy production, proscribing its use in other major uses, such as storage systems. Fortunately, utilization in Li, Aℓ electrodes does not seem to be irreversible. Developing methods of husbanding lithium, and recovering it from electrodes and battery electrolyte would seem to be prudent.

Indirect Effects

Energy to Produce Materials: Unknown quantities of aluminum, steel and copper will be required. Recent reports by Battelle Columbus Laboratories (Ref. 68) state the unit energy costs (Table 13) of some of the materials needed for solar power development. Their numbers include the entire production cycle from mine face to product.

TABLE 13. ENERGY COSTS FOR SELECTED PRODUCTS (REF. 68)

Product	Energy Cost (kWhr./kg)
Aluminum Ingot	79.0
Portland Cement	2.5
Refined Copper	36.0
Glass Containers	5.6
Carbon Steel Castings	13.6
Refined Lead	8.7
Elemental Phosphorus	55.0
Sulfuric Acid	0.01
Zinc, Elemental	21.0

Certain of the photovoltaic semiconductors are byproducts of copper, aluminum, or zinc manufacture. However, the additional energy costs beyond Cu, Aℓ or Zn production required to produce Cd, Ga, As, etc., are not readily available.

Project Independence (Ref. 23) estimates 200 tons steel/MW peak, or 2.47×10^6 MWhr/GW_{pk} capacity to produce the steel alone. This would have to be multiplied by a capacity factor, depending on duty and installed performance.

Taking our previous estimates for glass and aluminum in the panels, assuming flat glass and glass containers have similar energy costs, and ignoring aluminum rolling mill energy costs, we have

$$4000 \times 10^6 \text{ kg glass}/GW_e$$

$$\text{equivalent to } 2.2 \times 10^7 \text{ MWhr}/GW_e$$

$$5100 \times 10^6 \text{ kg aluminum}/GW_e$$

$$\text{equivalent to } 4 \times 10^8 \text{ MWhr}/GW_e$$

These numbers correspond to 3/32 in. single glazing and 1/8 in. backside aluminum support only. Other uses of glass would be minimal unless CdS deposited on float glass prevails. Assuming energy costs are reflected in dollar costs, utility companies can decide on a rational basis whether it is cheaper to use glass backside support with thin film conductor, or aluminum. Estimates of the aluminum needed for transmission line conductors and towers can be made easily when siting is decided.

Lead for storage battery use (a dubious prospect) is estimated thus: suppose 60% of battery mass is lead, and storage capacity is 25 Whr/kg total. Then we find 207 MWhr. energy cost/MWhr. storage capacity, using Battelle's numbers. Sulfuric acid energy cost is trivial.

The energy cost for silicon has been determined by Battelle but was not quoted in Ref. 68.

Phosphorus energy costs might be non-trivial if InP should find application, but the data in Table 12 are inadequate to compute this.

Air Pollution to Produce Materials: To do this properly, one would combine projections of various types of solar electric power facility construction, projections of coal, oil, and gas fueled steam electric power generation with appropriate mixes of fuel characteristics, compliance schedules, changing primary standards and state implementation plans, etc. There are too many uncertainties now to make this a fruitful effort.

Let us assume (incorrectly) that all power needed to manufacture materials is produced in 32% efficient, pulverized bituminous, drybottom utility boilers. Further, let us assume 3% sulfur, 12% ash, 12,800 Btu/lb coal.

Reliable emission factors (Ref. 69) are available. Energy production would be 2.4 MWhr/ton of coal. Emissions before and "after" control are given below in Table 14. We assumed 90% efficient precipitators, and time-linear increase from zero to 100% flue gas desulfurization (time average ~50% control of SO_x).

TABLE 14. EMISSIONS (lbs/MW_e hr.)

Item	No Control	Time Average Control
Particulates	85.0	8.5
SO_x	48.0	24.0
NO_x	7.5	7.5

Using previously discussed energy costs, we find the air pollutant production presented in Table 15.

TABLE 15. SOME AIR POLLUTANTS PRODUCED DUE TO ENERGY COSTS OF MATERIALS PRODUCTION FOR SOLAR ELECTRIC FACILITIES, PER GW_e INSTALLED CAPACITY

Commodity	Particulates (10^6 lb)	SO_x (10^6 lb)	NO_x (10^6 lb)
Carbon Steel	21	59	19
Glass Glazing	187	528	165
Aluminum Back Panels	3400	9600	3000
Totals	3608	10,187	3184

Primary aluminum production will result in emissions of particulates (including particulate fluorides) and gaseous fluorides. Fluorides cause vegetation and livestock injury.

Emission factors for many unit operations and for a number of control options are available (Ref. 69). The combinations are too numerous to attempt application here. Generally, total fluorides emissions run 15 to 30 lb/ton uncontrolled and 0.02 to 5 lb/ton for various control options, for each of several unit operations. We anticipate fluoride emissions to be 0.3 x 10^6 to 30 x 10^6 lb/GW_e.

Similar uncertainties apply to direct emissions from steel manufacture (Ref. 69) including particulates, carbon monoxide, and fluorides. For example, CO emissions may run 3.6 x 10^6 lb/GW_e capacity if electric arc steel is used, but negligible in the case of BOF production.

Glass melting produces particulates and fluorides. Perhaps 9 x 10^6 lb particules/GW_e capacity would be an upper limit, since control strategy should improve. Fluoride emissions may be less than 90 x 10^6 lb/GW_e, assuming improved control strategy.

Direct emissions of cadmium during smelting, refining, sulfide manufacture, purification, solar cell manufacture, etc., are all significant problem areas. Fleischer et al (Ref. 70) have performed an extensive review for the NIH Panel on Hazardous Trace Substances. Photovoltaic material manufacture was not considered, although base metal smelting was, since almost all cadmium is a byproduct of zinc, copper and lead smelting.

The data suggest that probably nearly all airborne cadmium is due to man's activities. Only inadequate data are available on the fate of airborne cadmium and its residence time in the atmosphere. Urban areas are found to have concentrations from 100 to 400 ng/m^3. The sources are thought to be primarily metallurgical operations. Table 16 presents esti mates based on production data and assumptions on losses and fates of waste streams. The work is by Davis et al as quoted in Ref. 70. No measurements were involved and some of the input assumptions have been questioned (Ref. 70).

Tables 17 through 20 present some analytical data from flue dust precipitator dusts and other waste streams in zinc beneficiation operations. Clearly a large increase in atmospheric cadmium levels will accompany increases in zinc production regardless of photovoltaic needs unless zinc smelter emissions are controlled more effectively. A mixed blessing is that the major fraction of zinc smelter cadmium emissions accumulates in the surrounding soil, where it penetrates deeply (Ref. 70). Figure 22 presents data of Miesch and Huffman (as quoted in Ref. 70) for soils near a smelter which had been operating for 80 years. Naturally this creates a potential for surface water and ground water contamination, although little is known about the fate of Cd in the hydrologic cycle. It also creates a potential for contamination of vegetation used as foodstuff by man and by livestock. For further details, the reader is urged to review the report by Fleischer et al (Ref. 70) since it is the most comprehensive review of environmental cadmium in existence.

Particularly if CdS photovoltaic material should become a high demand commodity, we can expect the price to be driven up. If this should happen, we might anticipate some smelters would adjust their operations to improve by-product recovery of cadmium, to the benefit of atmospheric quality.

TABLE 16. ESTIMATES OF ATMOSPHERIC EMISSIONS OF CADMIUM IN THE U.S. FOR 1968 (REF. 70)

Item	Cd, lb x 10^{-3}
Processing:	
Mining and ore processing	0.53
Smelting	2100.00
Reprocessing of metals	33.53
Electroplating	Very low
Pigment manufacture	21.00
Plastic manufacture	6.00
Alloys	5.00
Battery manufacture	0.40
Miscellaneous	1.13
Consumptive uses:	
Wear of automobile tires	11.40
Burning of oil, motor vehicles	1.82
Fungicide use	0.50
Fertilizers (superphosphate)	0.91
Steel scrap reclamation	2000.00
Radiator scrap reclamation	250.00
Plastic and pigment incineration	190.00
	4622.22 (= 2300 tons)

Until a better unit operations analysis and material balance data for smelting and for CdS production are available, quantitation of atmospheric emissions seems hopeless. Davis' results (Table 16) cannot be scaled validly. For example, his estimate for smelting emissions represented about 20% of current production (Ref. 70).

We have no comparable study of gallium. Such a project would be valuable, especially if it appeared that gallium arsenide would find massive application in photovoltaic generating stations (or geosynchronous satellite microwave transmission). Not one reference to gallium was found in the pollution abstract literature for the period 1973-75, for example.

TABLE 17. COMPOSITION OF ORE CONCENTRATE AND REPRESENTATIVE SAMPLES OF FLUE DUSTS FROM ROASTING AND SINTERING OPERATIONS (REF. 70)

Sample	Zn/Cd	Cd, %	Zn, %	Pb, %	Fe, %	Cu, %	S, %
Ore concentrate	256	0.18–0.20	45.9–52.6	1.8–2.9	6.7–10.8	0.6–1.6	25.6–32.2
Flue dust from roasting furnace	246	0.1–0.18	30.5–38.9	2.5–5.0	4.8–6.3	0.7–1.0	15–19
Dust from electrostatic precipitators from roasting furnace	48	0.5–0.66	22–33	20–34	3.1	0.35	~16
Flue dust from sintering machine	98	0.55	54	2.1	—	1.2	3.0
Dust from sintering machine collected in cyclone	136	0.27–0.55	53.4–58.1	1.6–3.1	—	1.1	4.3–5.5
Dust in exhaust from cyclone	5	3.5–8.8	22–44	95–37.1	—	0.22	7.1
Agglomerate	356	0.16	60.1	1.6	9.6	1.28	1.37

TABLE 18. COMPOSITION OF ZINC AND CADMIUM COMPOUNDS IN THE DUST FROM AN ELECTROSTATIC PRECIPITATOR OF A ROASTING PLANT AS DETERMINED BY SOLVENT EXTRACTION (REF. 70)

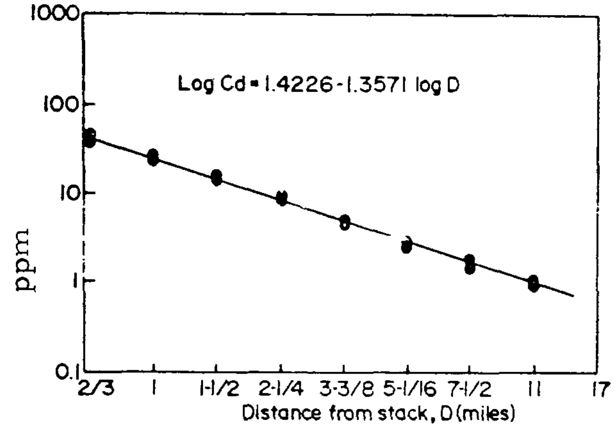
	% Extracted		
Solvent	Cd	Zn	Compounds extracted
Water	69.0	67.0	Sulfates
3% H_2SO_4	8.6	7.3	Free oxides
10% H_2SO_4	14.5	14.0	Ferrites ($CdO \cdot Fe_2O_3$, $ZnO \cdot Fe_2O_3$)
Residue	6.7	13.9	Sulfides

TABLE 19. DISTRIBUTION OF CADMIUM IN PRODUCT STREAMS FROM COPPER SMELTERS OF DIFFERENT DESIGNS (REF. 70)

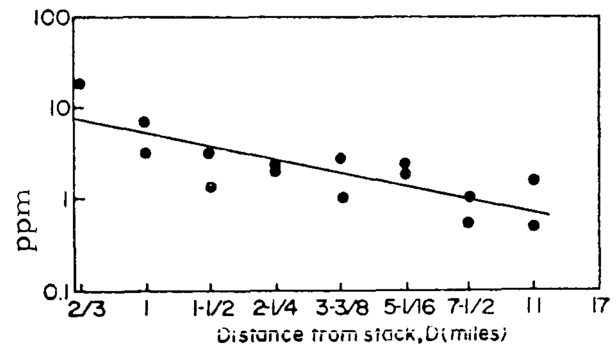
Stream	Cadmium recovery, %	
	Reverbatory smelting	Blast furnace smelting
Converter matte	49.1–56.3	38.4
Dust collected	6.8–9.2	22.9
Waste slag	7.1–12.6	16.6
Gas losses	29.1–29.8	22.1

TABLE 20. DISTRIBUTION OF CADMIUM IN BESSEMER PROCESSING OF MATTE FROM REVERBATORY AND BLAST FURNACE SMELTING (REF. 70)

Stream	Cadmium recovery, %
Crude copper	—
Converter slag	35.3
Flue dust	6.2
Gas losses	58.5



Cadmium contents of soil samples at depths 0–4 in. as a function of distance from smelter stack. Data of Miesch and Huffman



Cadmium contents of soil samples at depths 6–10 in. as a function of distance from smelter stack. Data of Miesch and Huffman

Figure 22. Soil contamination by airborne cadmium (Ref. 70).

Arsenic exists in atmospheric particulates primarily in the form of inorganic oxides and arsenates (Ref. 71). Atmospheric As_2O_3 concentrations as high as 1.7 $\mu g/m^3$ have been measured 3 km from a copper smelter (Ref. 72).

Literature on atmospheric arsenic exists because of interest by EPA, Public Health Service and State authorities' interest in copper smelting, for example. Clearly it would be advantageous to EPA and ERDA were a careful review of atmospheric arsenic emissions performed with emphasis on emission factors for unit operations, from smelting to photovoltaic panel fabrication.

An expanding body of literature exists concerning distribution of trace metals as functions of particle size, and even radial distribution within particles (Ref. 73). Arsenic and cadmium are found preferentially in fine particles in the respirable range. This is a particle size range which is particularly difficult to control. Natusch (Ref. 73) and others postulate that a volatilization-adsorption mechanism may be responsible for the preferential distribution of toxic heavy metals in finer particulates. This is a particularly unpleasant suggestion because high temperature processes are basic to smelting and beneficiation, and because we have evidence of preferential Cd volatilization (Ref. 70) in zinc smelting.

Natusch (loc cit) suggests that a volatilization-adsorption process could be exploited to develop a control system. He proposes preferential adsorption of volatile heavy metal species onto large, easily collectable heat stable particles deliberately introduced into flue gas streams.

If electronic grade cadmium sulfide and gallium arsenide become major commodities, it will certainly be necessary to investigate improved control technology, especially in the fine particle range. Both EPAand OSHA may find it useful to maintain close surveillance of the emissions and control technologies in these new industries.

Methods of sampling and analysis of toxic trace metals in atmospheric particulates are well developed and improving (Refs. 71, 74, 75). Gallium, however, has been overlooked. Many methods can be developed by elaboration of water analysis methods (Ref. 76) using bubblers containing appropriate absorbing reagents.

Air Pollution Prevented by Not Burning Fuels: It may be invalid to assume that any air pollution will be prevented by solar power development in the intermediate term. Even the most optimistic projections in ERDAs scenarios (Ref. 1) predict solar electric's contribution to be less than 2% of that of coal.

However, it is straightforward to calculate the emissions which would have occurred were no solar electric capacity developed, and fossil fuel combustion filled the gap. Assume 3% sulfur, 12% ash, 12,800 Btu/lb coal burned in 32% efficient dry bottom pulverized coal utility boilers. Assume 90% efficient precipitators (Ref. 69) in some distant time when the electric utility industry has achieved system-wide 90% flue gas desulfurization. The consequences are given in Table 21.

TABLE 21. HYPOTHETICAL "POLLUTANTS PREVENTED" BY SOLAR ELECTRIC SUBSTITUTION FOR COAL FIRED UTILITY GENERATION (See text for fuel parameters)

Pollutant	Emissions Prevented (lb/GWhr) No Control	Emissions Prevented (lb/GWhr) Control
Particulates	85,000	8,500
SO_x	48,000	4,800
NO_x	7,500	7,500

These numbers need to be multiplied by solar system capacity, capacity factors, etc.

It is probably fair to assume that by the year 2000, for example, Federal and State stationary source regulations, as well as control technology will be very different.

Water Pollution to Produce Materials: This subject has three major aspects: (1) surface water degradation and groundwater disturbance due to coal, zinc, copper and bauxite mining; (2) water pollution related to ore roasting, smelting and refining, and (3) waste water discharges in CdS and GaAs production and device fabrication.

Most bauxite is imported. Further, solar development is not likely to enormously increase aluminum production. Copper and zinc mining is outside the scope of this report, and it is not clear that increased Cd and Ga demands will necessarily increase aluminum, copper and zinc mining. Coal mining will be treated in a later section.

Fleischer (Ref. 70) indicates that the behavior and fate of cadmium in the hydrologic cycle is largely unknown. A large but still inadequate literature on the aquatic ecology of cadmium exists. The current literature suggests that there is no interest at all in Ga and In, and surprisingly little in As.

Introduction of cadmium into surface waters due to mining and smelting is significant. In addition, great quantities of material are disposed of in slag heaps, dross disposal, dumps, etc. Ultimately, some fraction of this is leached into surface and ground water. Table 22 and Fig. 23 due to Fleischer et al (Ref. 70) present one estimate of the problem.

Much more remains to be done in this area. Fortunately, solar electric development will be slow at first, so that some field research can be performed. Smelters and beneficiation plants have been in existence in the U.S. long enough that baseline data may be difficult to obtain, but steady state concentrations in polluted natural waters can be investigated.

TABLE 22. ESTIMATED RATES OF EMISSION OF CADMIUM DURING PRODUCTION AND DISPOSAL OF CADMIUM PRODUCTS FOR 1968 (Ref. 70)

Item	Mining and ore concentration, tons/yr	Primary cadmium production, tons/yr	Electroplating, pigment and plastic formulation, tons/yr	Coal and oil combustion, tons/yr	Cadmium-plated metals, tons/yr	Pigment, plastics, and miscellaneous* tons/yr	Alloys and batteries, tons/yr	Total tons/yr
Air contamination	---	930	---	120	500	90	40	1680
Water contamination	3000	240	300	---	---	---	---	3540
Soil contamination	---	---	---	---	---	---	---	---
Accumulation in service	---	---	---	---	1420	2080	880	4390
Land disposal (dumps, land fills, slag pits, mine tailings)	300	310	---	360	500	490	220	2180

*Losses during use and disposal.

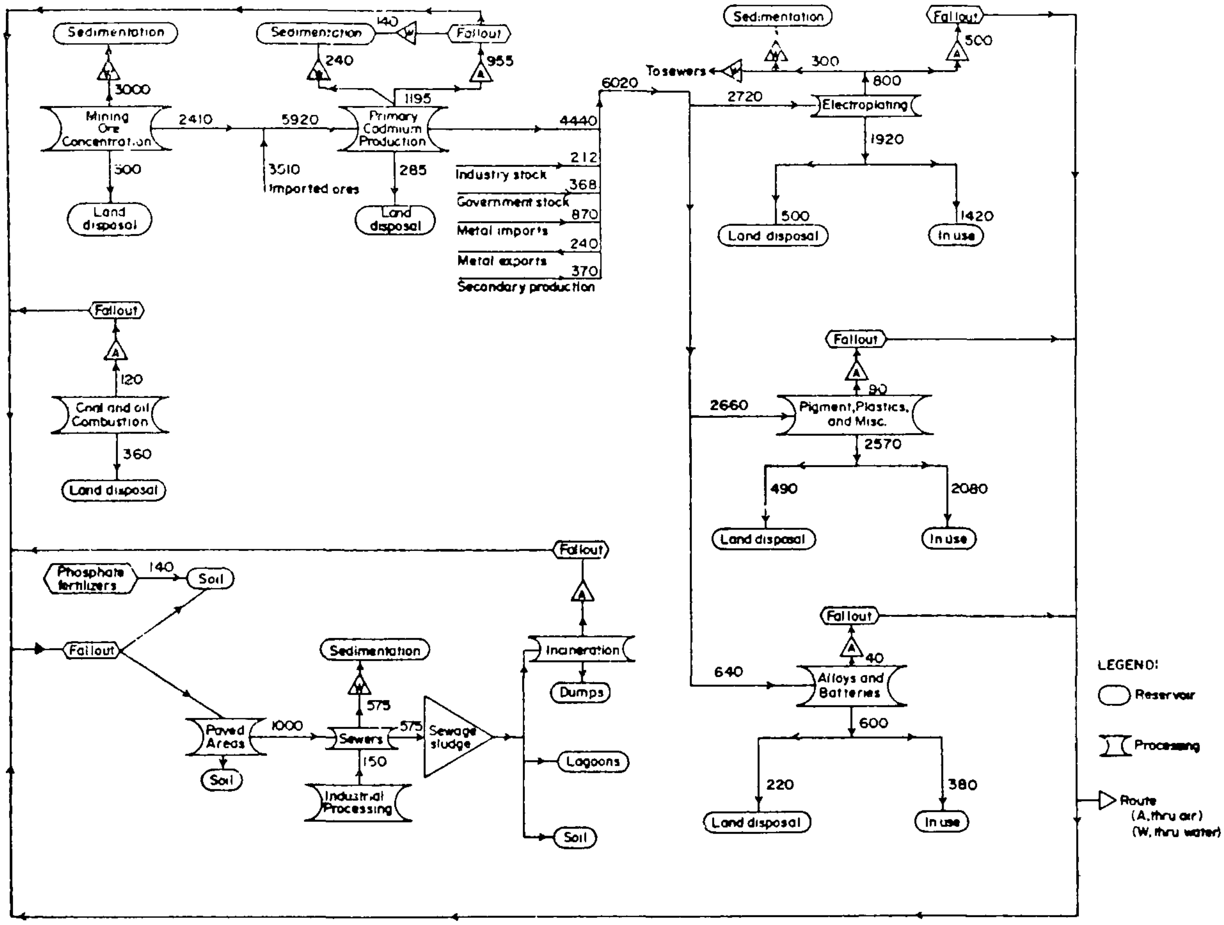


Figure 23. Rates (tons/yr), routes, and reservoirs of cadmium in the environment (Ref. 70).

Although Cd appears to be resource limited clearly CdS solar cells will see major use in pilot and demonstration plants in the near and intermediate term (Ref. 14). Therefore, it is urgent that an appraisal of the environmental effects of CdS production and cell manufacture be made available.

We recommend that such a study be performed soon for CdS and perhaps GaAs. It may be premature, however, to place a high priority on studies if InP, CdTe, and $CuInSe_2$ manufacture. A study of Si manufacture would be highly desirable even though Si is not identified as a pollutant. Si halides used in vapor deposition could cause both atmospheric and waste water releases if adequate control technology is not applied.

Avoidance of Coal Mining: We indicated in a previous subsection that solar development might not replace coal fired utility boilers in the intermediate term. Nevertheless, the potential exists if solar electric facilities are able to achieve a market penetration which outstrips the opening of coal mines and construction of fossil fuel fired electric plants.

Figure 24 depicts coal reserves in the western states. Most areas are unsuitable for coal stripping, although very large coal stripping operations

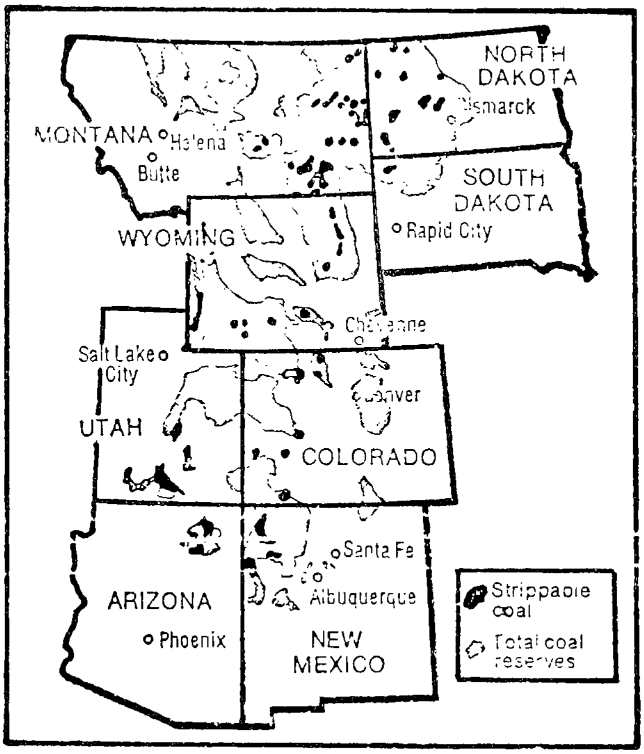


Figure 24. Potential coal mining areas in the Western states (Ref. 77).

do exist or are being opened in Montana, North Dakota and Wyoming, particularly. This is a mixed blessing. Mining is the second most dangerous occupation with an annual fatality rate of 71 per 100,000. Certainly, deep coal mining is more dangerous than surface mining. Avoidance of coal mining will save lives and prevent crippling accidents. Industry figures must exist to quantify this.

Other effects of coal mining and coal use now evident in the East which will soon be common in the West:

- Disposal of overburden
- Erosion of slopes
- Landslides
- Mine acid drainage ("yellow boy")
- Coal haul road erosion ("red dog" roads)
- Gob pile leachate
- Gob pile burning
- Loss of topsoil
- Lost agricultural productivity
- Growth of low income shanty towns
- Siltation of surface waters
- Disturbance of ground waters
- Air pollution from coal cleaning plants
- Energy use in coal cleaning plant thermal dryers
- Coal fines lagoons
- Limestone stripping and quarrying for mine acid control
- Limestone stripping and quarrying for flue gas desulfurization
- Scrubber sludge disposal
- Scrubber energy consumption
- Precipitator energy consumption
- Fly ash disposal
- Bottom ash disposal
- Highway damage
- Diversion of resource from coal conversion
- Lost aesthetic values

Presently many utility plants in the Western states use natural gas. Table 23 presents the fuel mix in the area. We know natural gas combustion will not continue for long. These plants will either be converted to coal (some to oil), or retired in favor of new nuclear, coal, solar, etc.

TABLE 23. FUEL MIX AT ELECTRIC GENERATING PLANTS IN THE WESTERN U.S. (REFS. 78, 79)

Region or Utility	Ref.	Percent Generation by Fuel				
		Coal	Oil	Gas	Nuclear	Hydro and Other
Region, 1973:		Percent of fossil only:				
West North Central	78	60.8	2.2	37.0	—	—
West South Central	78	3.2	6.0	90.8	—	—
Mountain	78	60.2	8.4	31.4	—	—
Pacific	78	5.8	47.0	47.2	—	—
Utility, 1975:		All "fuels" considered				
Central and South West	79	—	—	96	—	—
Gulf States Utilities	79	—	—	96	—	—
Houston Lighting and Power	79	—	—	96	—	—
Oklahoma Gas and Electric	79	—	—	99	—	—
Public Service, Colorado	79	62	—	33	—	—
Southern Cal. Edison	79	15	40	15	—	20
Texas Utilities	79	22	—	77	—	—

Nationwide, 492.6 million tons/yr of new coal capacity are to be opened by 1985 (Ref. 80). The mix is about 232×10^6 tons deep and 284×10^6 tons strip. Different rounding and inclusion of auger mining and new mines opened in 1975 make the figures irreconcilable. The data are summarized in Table 24. The names and locations of the mining companies, their mines, the destination of their products, and the year-by-year capacity expansion are all detailed in Ref. 80.

It is obvious that even though a relatively small fraction of the areas in Fig. 24 appear suitable for surface mining, stripping is the major expanding segment of the industry, and steam coal usage is the major destination.

At some stage in solar development this expansion of coal mining may be deterred or eliminated, or the coal will be released for use in conversion plants and chemicals industry. To the extent that this happens, lives will be saved,* land will be saved, air and water pollution will be reduced, and a non-regenerable resource will be released to more valuable uses.

*One estimate is that 4,480 fatalities will have occurred in deep mining and 1,200 in surface mining of coal in the period 1970-2000 (Ref. 81).

TABLE 24. NEW COAL MINE DEVELOPMENT IN THE WEST BY 1985 (REF. 80)

	Deep Capacity 10^6 tons/yr	Strip Capacity 10^6 tons/yr	Destination (10^6 tons)		
			Metallurg.	Steam	Gasification
Arizona	—	8.0	—	8.0	—
Colorado	10.2	13.6	4.5	9.3	10.0
Kansas	—	0.8	—	0.8	—
Montana	—	55.5	—	55.5	—
New Mexico	—	17.6	—	17.6	—
No. Dakota	—	30.1	—	30.1	—
Texas	—	19.7	—	19.7	—
Utah	29.5	—	—	29.5	—
Wyoming	3.3	120.9	—	110.2	14.0

We believe it would be useful to assemble and collate an inventory of fossil fuel fired plants in the regions hopefully to be the principal service area for solar plants prior to the year 2000. This inventory should indicate present fuel mix, suitability for conversion to coal, estimated retirement date, heat rate, owner's plans for it and its replacement, etc.

Much of these data probably exist in EPA and ERDA files and in the open literature. Such an inventory would be very useful in determining the indirect environmental effects (beneficial and adverse) arising from new energy sources.

<u>Labor, Modular Construction, and Population Shifts</u>: Project Independence (Ref. 23) figures for an accelerated photovoltaic production schedule are given in Table 25.

TABLE 25. WORKERS IN PHOTOVOLTAIC PRODUCTION: PROJECT INDEPENDENCE ACCELERATED SCHEDULE (REF. 23)

Year	Capacity, MW_{pk}, Produced in Year	Workers Inclusive of Construction
1980	5	1,932
1985	100	38,700
1990	1000	430,000
1995	1000	1,720,000
2000	1000	3,440,000

No separate estimates of construction workers is included. It would be a useful number to have. A feature of photovoltaic utility systems is the prospect of factory construction of modules. Thus, we do not anticipate large population shifts to the Southwest due to device and panel fabrication. Population shifts will occur wherever mining, smelting, materials production, and panel fabrication occur. Population shifts to solar areas will be mostly due to construction workers and operating personnel.

Additionally, there will be substantial demands for transportation workers, construction workers, and municipal and business employees servicing construction towns. The latter categories may be large. To analyze the situation further is outside the scope of this report. Nevertheless, it is a very important consideration which EPA, ERDA, HUD, FHA, DOT and numerous other Federal agencies will want to study in a timely manner.

Transportation Demands: Increased transportation demands have been alluded to previously. This area of concern is also outside the scope of this report, but needs study. Siting of production facilities may need to be influenced by transportation requirements as much as any other criteria.

Toxicology and Industrial Hygiene: An enormous labor force is envisioned according to Table 25. Large new commodity markets are to be created. As a consequence of the known toxicity of some of the photovoltaic semiconductor materials, extraordinary numbers of workers and families will be put at risk. The numbers involved probably dwarf the work force potentially exposed to uranium and plutonium during the nuclear industry's seminal years.

How prepared are we to deal with the industrial hygiene problems? The famous Poison Control Center in Atlanta has nothing retrievable in its files on gallium, indium and antimony (Ref. 82). EPA is doing some in-house work on indium, and has contracted with A.D. Little to prepare a report on antimony (Ref. 83). NIOSH has been active, also. In 1976 a new edition of the NIOSH Manual of Analytical Methods will appear (Ref. 84). The following list summarizes the analyses in the current edition and the expected 1976 edition.

NIOSH Manual of Analytical Methods (Ref. 85)

x = current edition

● = 1976 edition

Element (Analyte)	Material (Matrix)		
	Blood	Urine	Air
Cadmium	●	●	●x
Arsenic	●	●x	●x
Gallium		●	●
Antimony	●	●x	●
Indium	●	●	●

Most methods will use anodic stripping voltametry.

A reissue of the criteria document for arsenic is coming out (HEW 75-149), with an atmospheric reference of 2 $\mu g/m^3$, 15 min sample (Ref. 85). A cadmium criteria document is now in preparation. Fine particles analyses and potable water analyses for some constituents of photovoltaic materials have been published (Refs. 74, 75, 76).

A large literature exists on toxicology (and environmental toxicity) of arsenic and cadmium. Gallium and indium are known to be toxic, in spite of their positions below aluminum in the periodic table (Refs. 86, 87, 88). Antimony was the subject of a very old review (Ref. 89). To a surprising degree the data are for laboratory animals rather than humans. Fleischer et al. believe threshold values for cadmium are too low (Ref. 70).

Except for cadmium and arsenic, little is known about the effects of these materials on aquatic biota, nor is much known about low level chronic inhalation toxicity on humans, domestic animals, and livestock.

If it appears that gallium arsenide is to receive much application, strenuous efforts should be made to develop much better information on work place safety and environmental toxicity. It is probably not too early to begin such studies now.

SECTION V

CONCENTRATOR SYSTEMS

CONCENTRATOR TECHNOLOGY

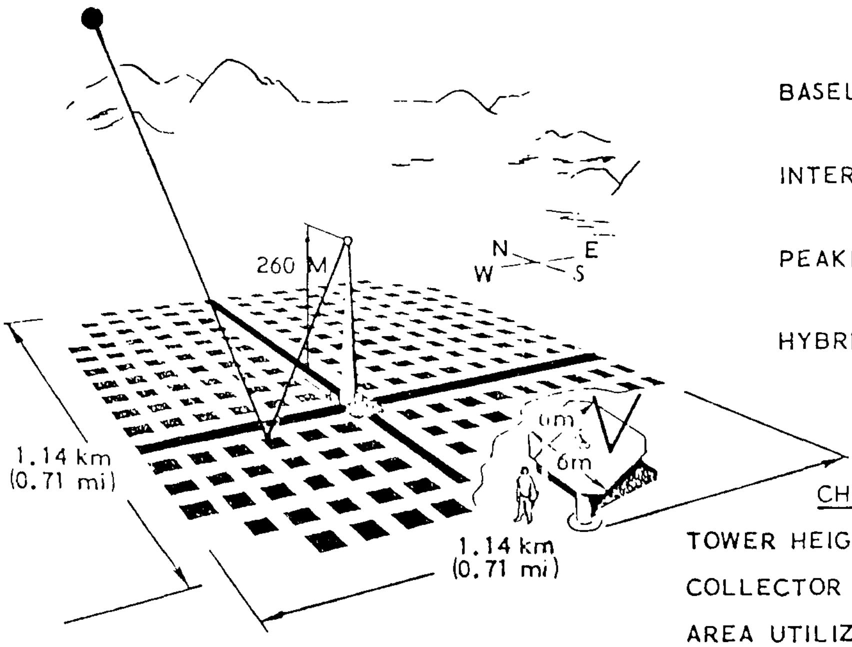
The basic concept of concentrator technology is to collect solar radiation over the land area required by the plant rating, and concentrate it onto a manageably small area. The concentrated radiant energy is then used to produce steam directly, or to heat a heat-transfer fluid, or to irradiate photovoltaic cells. A heat transfer fluid may be used to convey energy to a steam boiler; to supply process heat or space heat; or to store heat or convey energy to a storage medium. Various combined concepts exist. We will consider here only power conversion systems, and not process or space heat systems. Two generic types of power conversion concentrator system exist – central receiver and distributed.

In the central receiver, solar energy is transmitted optically from an array of collectors to a central, tower top receiver ("power tower"). A boiler may be located on the tower top; or on the ground. In the distributed system, a heat transfer fluid must circulate from the tower top to the boiler, or a reflector redelivers the radiant energy optically back to ground level (Fig. 25). In distributed systems (Fig. 26), solar collectors are connected by long piping runs (Ref. 90).

Collector concepts include fields ("farms") of sun-tracking flat mirrors ("heliostats") (Fig. 25), tracking parabaloids or cylinders, fixed cylinders (Fig. 26) or fixed Fresnel lenses, either circular or cylindrical. Cylindrical receivers require the heat transfer fluid pipes to be arranged along and track the linear focus of the reflectors, which sweeps across a cylindar arc in the diurnal cycle. This is a relatively simple motion. Tracking paraboloids are required to follow the sun in two degrees of freedom.

For useful operation of turbogenerators, temperatures exeeding 600 K are desirable. Steam turbogenerators operating as low as 600 K exist; this is comparable to the design temperature of pressurized water nuclear plants (Ref. 90).

Tracking parabolic collectors can produce temperatures of 800 K. In fact, concentration ratios of 1000X and more are achievable now using tracking parabolic dishes. Therefore, in principle at least, concentrator systems may operate at the highest temperatures permitted by materials properties and demanded by turbogenerator design. From the standpoint of land efficiency as well as steam temperature, tracking paraboloids would be best. However, there are experts who believe the system is too cumbersome, too



100 MW_e PLANT

BASELOAD	3 MODULES (12 hr storage)
INTERMEDIATE	2 MODULES (6 hr storage)
PEAKING	1 MODULE (3 hr storage)
HYBRID	1 MODULE (1/2 hr storage)

CHARACTERISTICS

TOWER HEIGHT	260 m
COLLECTOR AREA	0.5 km^2/MODULE
AREA UTILIZATION	38.6%
TOTAL LAND AREA	1.3 km^2/MODULE
No. OF COLLECTORS	15,400/MODULE
SIZE OF COLLECTORS	32.4 m^2

Figure 25. Solar thermal conversion: central receiver concept. Schematic diagram of solar tower concept. The sun's energy is reflected by heliostats to a receiver atop a high tower and a coolant circulates through the receiver bringing the reflected energy to the ground (Ref. 40).

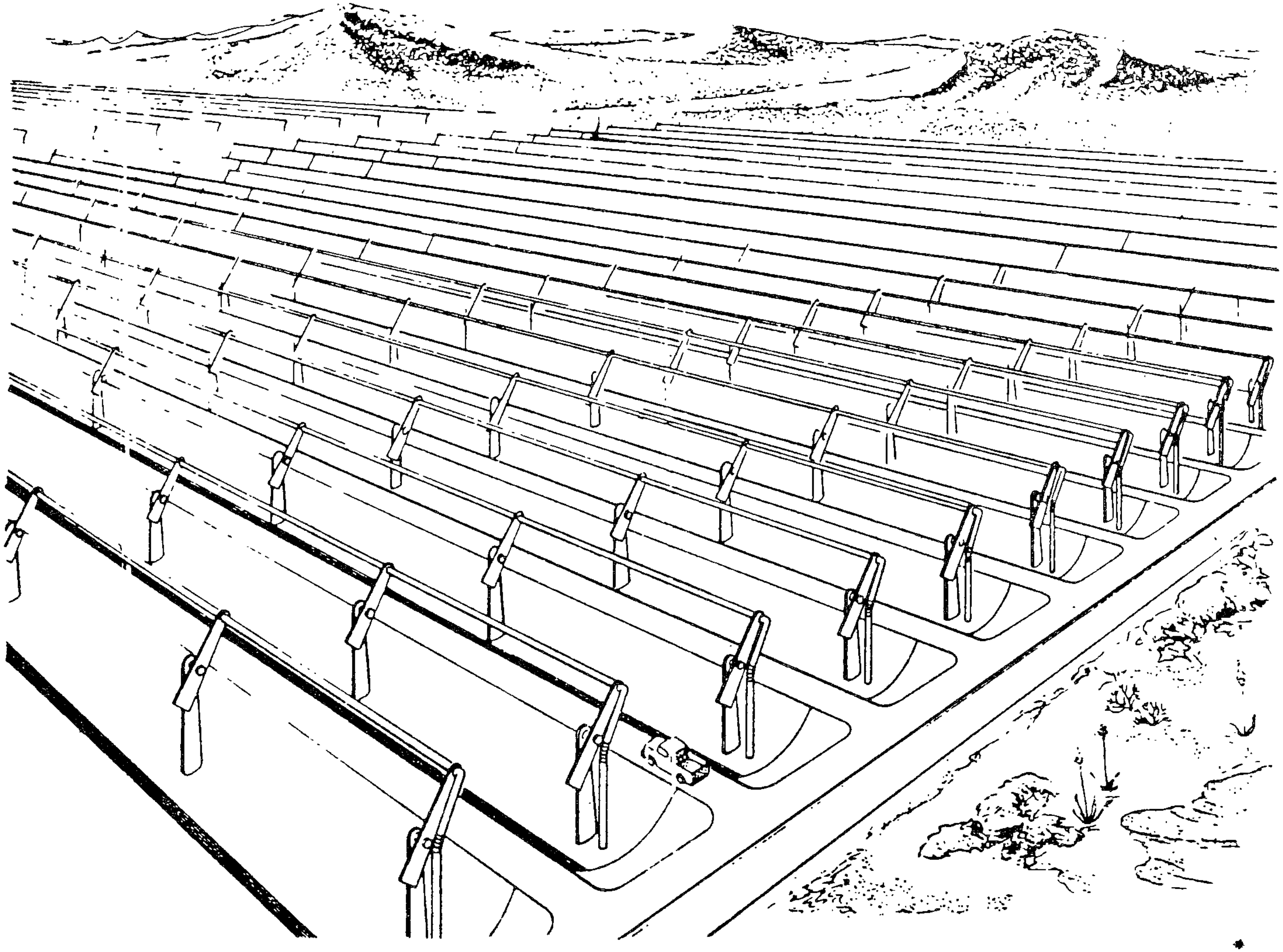


Figure 26. Fixed mirror solar farm (Ref. 36).

delicate, and too difficult to control. They believe the tracking parabolic collector is not a serious competitor (Ref. 36).

Serious objections have been raised also concerning the idea of installing a steam boiler on top of a power tower. The authors of the Dow report, for instance (Ref. 50) state:

> "For those who have operated a high temperature boiler at ground level, the thought of running a similar unit 500 ft in the air is appalling. New maintenance systems will need to be devised for such operations as replacing burned out or plugged tubes... Just the mechanical suspension of such a unit to permit human access without blocking radiation appears to be a major challenge."

We might add that there could be substantial safety problems in performing maintenance near the focus of a 100 MW field!

Two surviving central receiver concepts are thought to be especially viable. In one, individually controlled tracking heliostats (flat mirrors) focus onto a central reflector at the top of the power tower, which then refocuses the radiation onto a ground level converter. The other scheme requires the hot heat transfer fluid to bring the energy to the ground. In both cases, the steam boiler and turbogenerator would be ground based. Heat transfer media may be steam or molten metals. Sodium has been proposed.

Table 26 presents some design dimensions for a power tower — collector form, which supplement those of Fig. 25.

The power rating implied in Table 26 may not be realistic, for it is not likely that there will be 100% land coverage.

If we assumed 40% coverage and, 30% conversion efficiency, we get the output values of Table 27.

The region receiving an average solar flux of 200 W/m^2 includes San Francisco, Salt Lake City, Denver, Little Rock and Atlanta.

Reflector materials may be glass, polished metal, or metallized plastic. Much current research is devoted now to optimizing performance and reducing costs of reflectors. Indeed just as with photovoltaic generating station concepts, cost reduction has assumed overriding importance. Fixed cylindrical or linear Fresnel reflectors (Fig. 26) may be composed of asphalt or concrete onto which is impressed a metallized plastic or metal foil reflective material. Clearly large quantities of reflector materials will be required to satisfy any design requirements. These material requirements and other data have been combined by one panel (Ref. 40) into an estimate that 100 mi^2 of solar power tower farm installed per year would correspond to one production facility requiring three float glass lines and 1% of U.S. annual steel production.

TABLE 26. CENTRAL RECEIVER SOLAR POWER PLANT REQUIREMENTS (REF. 36)

Item	Measurement					
Tower height (m)	100	150	200	300	450	600
Field diameter (km)	0.4	0.6	0.8	1.2	1.8	2.4
Equinox power (MWth)	33	73	132	293	660	1172
x 30% — (MW_e)	10	22	40	88	200	352
	Mirror Size (meters)					
Number of mirrors:	Too Small					
144,000	0.67	1.0	1.3	2.0	3.0	4.0
64,000	1.0	1.5	2.0	3.0	4.5	6.0
36,000	1.3	2.0	2.7	4.0	6.0	8.0
16,000	2.0	3.0	4.0	6.0	9.0	12.0
7,000	3.0	4.5	6.0	9.0	13.5	18.0
4,000	4.0	6.0	8.0	12.0	18.0	24.0
1,800	6.0	9.0	12.0	18.0	27.0	36.0
800	9.0	13.5	18.0	27.0	40.0	54.0
				Too Large		

TABLE 27. CENTRAL RECEIVER SOLAR PLANT GENERATION POTENTIAL (REF. 36)

Average Solar Flux (W/m^2)	Average Percent of Possible Sunshine	Average Power Output (MW/mi^2)
260 (Highest)	85	91
200 (Average)	65	70
140 (Lowest)	45	49

A further elaboration of the concentrator concept is exemplified by the Sandia Laboratories combined photovoltaic-thermal electric system (Ref. 23). A linear collector mirror, either a parabolic or circular cylinder, concentrates radiation onto photovoltaic cells which are in thermal contact with a circulating fluid in a heat transfer loop (Figure 27). A silicon solar cell loses output at a rate of about 0.5%/°C. Therefore, efficient heat transfer is needed so that the combined converter actually achieves a net efficiency sufficiently high to justify the added complexity.

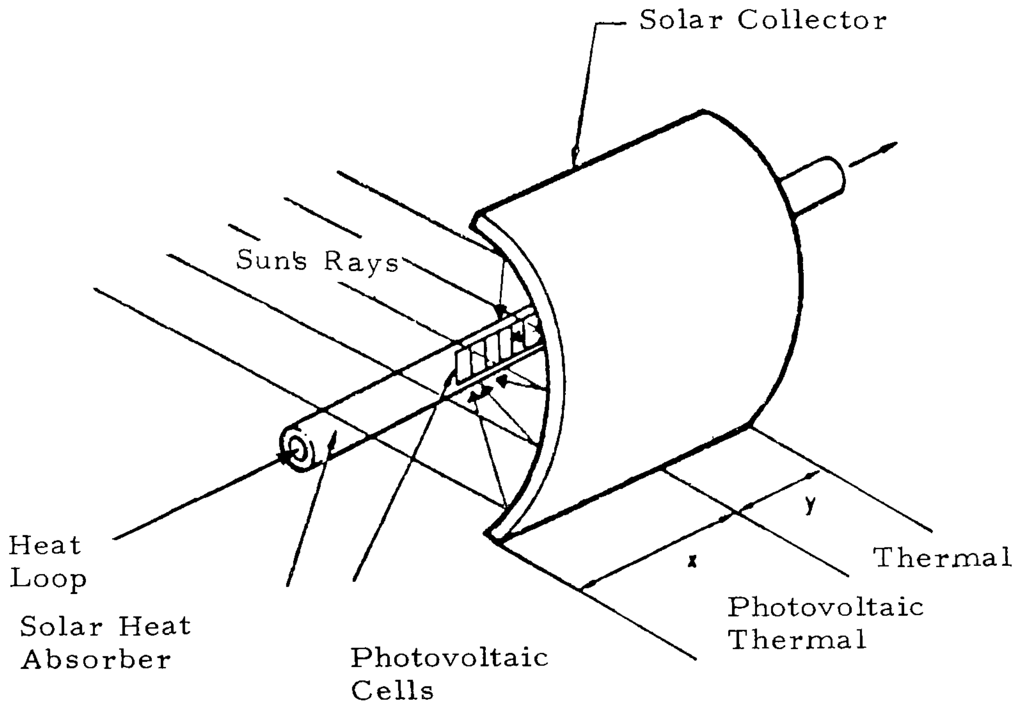


Figure 27. Combined photovoltaic and thermal-electric system (Ref. 23)

ENVIRONMENTAL IMPLICATIONS

Many of the environmental effects of concentrator systems have been discussed explicitly or implied in the photovoltaic chapter. We will review the situation here.

Siting and Grid Dispersal

Photovoltaic generating stations could be sized almost arbitrarily to meet the requirements of specific load centers or of central generating facilities. The principal constraint would be imposed by cost and design of peripheral equipment. By contrast, concentrator conversion systems have economies of scale which preclude small scale, grid dispersed application.

Steam electric generating facilities are simply not suitable for modular construction.

Even more restrictive is the water requirement. An exception is the photovoltaic concentrator systems. All other concentrator systems require a working fluid, usually steam and a cooling loop as well. Conventional wet, mechanical draft cooling towers are frequently envisioned. Thermal electric efficiencies comparable to those of coal plants are expected: 30 to 32%. Thus an ample supply of surface water is nearly essential.

Direct Effects

Surface Waters and Thermal Pollution: Heat rates comparable to conventional fossil fuel plants imply thermal discharges of the same magnitude for comparable plants. With these, we have blowdown, cooling tower chemicals, destruction of aquatic organisms at intake screens and in the cooling loop, resultant BOD, salination, and the host of other tower effects. We do not have coal pile drainage, fly ash and bottom ash disposal, scrubber sludge leachate, coal fines lagoon drainage, etc.

Thus we avoid all of the feedstock related water pollution effects. On balance, solar concentrator "farms" look very good indeed when ample surface water is available.

Ground Water: The absence of toxic semiconductor materials is advantageous. It is possible that well water may be used for the cooling tower makeup. Effects of groundwater extraction (such as subsidence) will need site-specific investigation.

Land Use: Roughly speaking, land use requirements will be comparable to those of photovoltaic systems. We disregard differences of the order of 50% as being comparable to variations occasioned by currently discussed design alternatives. (See Figure 25 and Tables 26 and 27.)

Visual Effects: Power tower designs will have greater visual impact than a flat plate photovoltaic facility. Masts of 200 to 400 m high are discussed seriously. These are comparable to utility fossil fired stacks. Heliostat "farms" may create some glare which could be distracting when viewed from higher elevations. Interference with vision of aircraft flight personnel is conceivable and should be studied.

Terrain Effects: Earth moving and foundation preparation for the power house and power tower will approximate the activities during construction of a conventional fossil steam electric plant. The heliostat or focusing reflector field will not require substantial earth moving.

Agriculture and Terrestrial Ecology: Because of the relative delicacy of tracking mechanisms, and possible machinery hazards to livestock, "multiple use" grazing is probably impractical. The shading effects discussed previously should be similar in the two systems. Shading, and humidity increases from cooling tower drift and fog, may create proliferation of previously uncommon flora.

Air Pollution: Aside from cooling tower emissions no air pollutant emissions can be identified in normal operation. Cooling tower drift will carry chemicals.

If exotic heat transfer media such as molten sodium are employed, accidental releases are possible. Ignition of a sodium spill would generate quantities of caustic particulates and create a severe hazard to emergency personnel.

Transmission Lines: This has been discussed previously.

Weather Modification: This has been previously discussed at length in this report. Power tower installations will simulate greater surface roughness than do photovoltaic or cylindrical distributed systems. Altered surface wind velocities and cooling tower plumes will create greater potential for microclimate change than previously discussed.

Noise: Unlike non-concentrating photovoltaic installations, concentrator steam electric facilities will have rotating equipment. Noise levels would be comparable to those experienced in conventional turbogenerator applications.

Radiation: No ionizing radiation sources are anticipated.

Historical, Archaeological, and Paleontological Values: Because of the delicacy of tracking equipment and personnel hazards, salvage archaeology probably cannot proceed after construction.

Accidents, Disasters and Sabotage: Seismic events, accidents, and deliberate mischief could cause rupture of sodium lines, if this metal were used for heat transfer. Ignition of the sodium could cause extensive personnel injury and equipment damage due to corrosive emissions and heat. Combustion of storage materials is conceivable. Fire propagation could be fierce if molded asphalt were used for fixed trough type collectors. Facility security can be ensured, but with greater expenditure than is now the case with more compact conventional facilities.

Resource Commitment and Depletion: No "exotic" materials are likely to be needed in any substantial quantity. Thin film selective coatings for reflectors are proposed. Gold and hafnium are candidates. A 1 GW_e plant might require one cubic meter of hafnium, or 1.5×10^4 kg (Ref. 7) representing 46% of 1970 domestic production. However, hafnium production is demand limited, not resource limited. World reserves at 1970 prices are thought to be about 280×10^6 kg of which U.S. reserves are about 113×10^6 kg (Ref. 62).

Energy storage requirements may be solved by pumped storage, since surface water is likely to be available at a solar steam electric plant. A hydrogen cycle system (discussed previously) is possible. But storage as sensible or latent heat is seriously proposed. Heat transfer fluid may be used. Another possibility is the use of phase change materials. Proposals to use $Na_2SO_4 \cdot 10\ H_2O$ and $Na_2S_2O_3 \cdot 5\ H_2O$ (Refs. 91) are not attractive because the phase change temperature is much too low for turbogenerator application.

Anhydrous Na_2SO_4 has been proposed. A 1 GW_e plant would require about 3×10^8 kg of this substance for a day's storage capacity (Ref. 7). Production of this quantity of Na_2SO_4 would not strain our reserves. Discussion of the vast variety of other storage materials is premature now. The interested reader should consult Ref. 92.

Indirect Effects: As for photovoltaic systems, much of the construction activity may occur in factories. Foil lined concentrator troughs cast in concrete or asphalt are exceptions. No especially toxic materials are identified now. Until design features are better established, it seems premature to discuss the environmental consequences of upstream manufacturing. Air pollutant emission factors for Portland cement manufacturing, concrete batching, steel, aluminum and glass manufacturing, etc., are all available (Ref. 69) as are estimates of energy required to produce these materials (Ref. 68). When materials estimates become available for specific installations, or even conceptual designs, waste stream analysis and energy expenditures may be calculated. (See pages 37 and 74 for discussions of possibly beneficial delays or avoidance of coal mining.)

SECTION VI

FLAT PLATE COLLECTORS
by P. O. McCormick

TECHNOLOGY ORIENTATION

Flat plate solar collectors have been in widespread use since the turn of the 20th century. Investigators have tried to take advantage of this abundant, clean, "free" energy source for a variety of uses, including:

- Domestic Water Heating
- Space Heating
- Agricultural Application (Drying, Curing, Water Desalination, etc.)
- Space Cooling and Dehumidification

Initially, the interest was principally in experimenting with a novel concept. However, in the 1920s, the use of solar hot water heaters became popular in areas where people wanted domestic hot water but lacked a convenient heat source such as natural gas. This application was mostly in the Southern U.S. (and other areas of the world such as Australia and Israel) where sunshine was dependable year-round. Ironically, this use of solar energy (at least in the U.S.) almost completely died out when alternate fuel sources became readily available.

None of the other applications have ever had widespread use though much experimentation has been done, especially in space heating and agricultural applications. Solar air conditioning has recently been the object of much research and a few demonstrations, but even the most optimistic proponents see widespread solar air conditioning as being several years away due to the high cost of heat driven air conditioning equipment (Ref. 93). Demonstration projects are now getting underway to apply solar heating to industrial process heat requirements and to agricultural product drying.

Current Technology

Current available flat plate collectors come in a variety of designs, determined primarily by the intended application. The basic solar collector that has been used since the turn of the century has a black painted metal absorber with one or two transparent covers. Traditionally copper is used for the absorber in liquid heating collectors while almost any metal is useable for air heating systems. Recently, there has been quite a substantial effort to make the absorbers of liquid heating collectors out of aluminum in order to reduce cost. But, while the aluminum manufacturers were trying to solve the corrosion inhibiting problem, steel absorbers have been making inroads into the collector market. The transparent cover can be anything that transmits light, but prevents outside air from blowing directly over the absorber which would take the absorbed energy away. Many transparent materials have been used, but glass tends to be the material that is used whenever a collector is designed to operate for any long period of time.

The next step up the development ladder for collectors has been the introduction of selective coatings, a coating that absorbs well in the visible spectrum but emits poorly in the infrared. The importance of selective coatings becomes very pronounced as the operating temperature of the collector gets above about 100 F (such as for solar air conditioning applications). A good selective coating can reduce the reradiation losses such that collector efficiency is doubled compared to flat black absorbers at elevated temperatures.

Convection suppression is also a means of increasing solar collector efficiency at high temperatures. The so called "dead" air space between the absorber and cover in a collector is by no means stagnant. Free convection currents are set up by the temperature difference between the cover and absorber. These free convection currents account for a large part of the energy lost from the collector. Devices such as transparent and reflective honeycombs, (to physically interfere with free convection currents) as well as evacuation of the airspace, are currently under development for convection suppression.

For a review of residential installation technology and solar architectural practice, see Steadman (Ref. 94) whose book contains illustrations of numerous existing solar homes.

Effect of R&D Efforts on Flat Plate Collector Use

Significant R&D activities are underway to increase flat plate collector efficiencies, particularly at high temperatures. These concepts (such as evacuated collectors, honeycomb convection suppressors, directionally selective surface, and highly selective coatings) will influence the utilization of solar collectors, particularly for solar cooling and process heat uses. The cost/performance ratio of currently available solar collectors, along with the $3000 price tag of a three-ton solar air conditioner, make residential solar cooling economically unattractive. With better collectors at reasonable prices, solar cooling of homes could be economically feasible. The lack of air conditioning capability is a substantial barrier to nationwide utilization of solar energy in homes because many people who might install a combined heating/cooling system, would not consider a heat-only system.

In any event, the major effect of R&D will be on the amount of solar collectors used. The projected utilization rate if 0.37, 5.6 and 29.7 x 10^8 m^2 in 1985, 2000 and 2020, respectively, derived from Refs. 4, 93, 95 and 96.

Solar Collector Manufacturers

There are many companies currently manufacturing solar heating components. A comprehensive list of manufacturers is available in Ref. 97 (which is the result of an industry-wide survey by ERDA) and Ref. 98. The following is an excerpt from these tabulations:

Corning Glass Works	Powell Brothers, Inc.
E&K Service Co.	PPG
Energex Corp.	Raypak, Inc.
Energy Conservation Systems	Revere Copper & Brass, Inc.
Energy Systems, Inc.	Reynolds Metal Co.
Fred Rice Productions	Rodgers & MacDonald, Inc.
Garden Way Laboratories	Shelley Radiant Ceiling Co.
Grumman Aerospace Corp.	SOL-R-TECH
Halmac Co.	Solarsystems, Inc.
Helio-Dynamics, Inc.	Stolle Corp.
Intertechnology Corp.	Sunearth, Inc.
Itek	Sunworks, Inc.
Kalwall Corp.	Tranter, Inc.
Northrup, Inc.	U.S. Solar Corp.
Physical Industries Corp.	Unitspan Architectural Systems, Inc.

Materials Used in Flat Plate Solar Collector Systems

The assessment of material uses for solar hardware must be largely subjective at this time because three major questions are unanswered:

- Can the corrosion problems associated with using liquid in a steel or aluminum absorber be solved to the satisfaction of the users?
- Can integral collector/roof structures be made more economically on site than collector modules made in a factory?
- Will combined thermal/photovoltaic collectors be employed in residential uses (cf. Fig. 6, para. 4.1.5)?

Liquid, rather than air, heat collectors are generally preferred because of pumping power difference, simplicity of heating system (ducting, etc.) and the much easier application of liquid systems to heat driven air conditioning systems. However, corrosion of liquid collectors is a very real problem. Most current users of solar collectors are utilizing copper absorbers (particularly those that are funded by the U. S. Government); this makes collector panels very expensive. Either steel or aluminum absorbers would be less expensive but most people are reluctant to buy collectors that may corrode in five years (as has happened many times). The solution to this problem will give rise to the use of common materials such as steel for the absorber.

The use of an integral solar collector/roof structure could, conceivably, reduce the collector materials to only that used in the absorber and cover. Amazingly enough, however, the only known research in this area (Ref. 99) is directed to producing prefabricated roofing panel/solar collectors, not on-site construction of solar collectors as part of the roof structure by building trades workers.

Based on these and other subjective auguments, the major materials requirements (including all solar-related hardware) are 0.35 lb Aℓ, 3.0 lbs steel, 0.5 lbs Cu, and 2.0 lb glass per square foot of collector.

Storage Systems

The type and size of storage systems for use with flat plate solar collectors is dictated by the particular use of the system. However, the following general characteristics are typical of all uses:

- Easy addition and removal of energy,
- Small energy losses, and
- Capable of storing energy at or above the temperature of use.

Historically, the preferred storage mediums have been water (with liquid heating collectors) and rocks (with air heating collectors). The technical merits of phase changes materials (PCM) and chemical change materials (CCM) (Ref. 91, 92, 100) offer significant technical advantages over water and rocks; their technical advantages never seem to outweigh their extra cost, however. Undoubtedly, there will be some applications where flat plate collectors will be used with either PCM or CCM storage, but the uses appear to be so few that they are not addressed in the environmental assessment. EPA may wish to watch the market penetration of PCM and CCM materials, but it would be premature to embark on a detailed environmental assessment here.

The storage mediums that are expected to be of greatest use with flat plate collectors between now and the year 2000 are:

- Treated Water: Water treated with 200-500 ppm of corrosion inhibitor is the most versatile medium. It will be widely used for applications in (1) domestic hot water heating, (2) residential and commercial space heating, (3) residential and commercial cooling (both as hot and cold storage), and (4) industrial process heat. For the process heat applications that require storage up to 120 C or so, a brine solution may very well be the most cost effective storage medium, even considering the corrosion problems. In many climates, an antifreeze solution may be desirable.
- Rocks: The value of an air collector/rock storage cannot be overemphasized when long life and dependable service are of prime importance. However, the use of rocks normally makes a bigger

impact on building space than other types of storage and is, therefore, best used in new construction rather than in retrofit. This is due to the larger size required for rock storage (compared to water) and the fact that air ducts are required rather than water pipes to put energy in and take energy out of the storage.

ENVIRONMENTAL ASSESSMENT

Siting

The major contribution that flat plate collectors can make toward providing energy to replace conventional fuels is in residential applications. This is not due as much to the energy requirements of space heating and cooling as it is due to the temperature required for other applications. Though there are many industrial processes that can make use of large quantities of heat, most of them require temperatures too high to be supplied by flat plate collectors (at reasonable efficiencies). Much of the process heat that is within the range of flat plate collectors is supplied by degraded steam at a very low cost per Btu. There are many legitimate uses for flat plate collectors in industry (minerals, agriculture, food processing, etc.) but the contribution of industrial applications to the use of flat plate collectors will remain small. Since the large industrial facilities are not likely to use flat plate collectors, there is not likely to be any large groupings of flat plate collectors as might be expected of photovoltaic or solar thermal power production.

There is the possibility that centralized collector farms may be used to provide the heating and cooling for a community or, certainly, for high density housing such as apartments and townhouses. Solar ponds, centrally located in a community, have been proposed as a low cost solar heating system. However, social problems and individual differences in comfort zones will keep community solar equipment from becoming too popular. There is also the technical problem of pumping energy (in the form of hot water, for example) over long distances.

In summary, then it can be assumed within some limits that solar collectors will be in use in direct proportion to the density of housing. Both commerical and industrial uses will pose exceptions, but housing and commercial buildings tend to grow up around industrial centers as a general rule. Solar collector use inside large cities is an exercise in futility. Not only is maintenance a difficult problem, but trying to ensure that solar collectors will have a view of the sun for 20 years in the future will be difficult. For large cities, it is much better to create power in a central solar electrical plant and pipe it into the downtown area. Thus the heaviest application for flat plate collectors will be in suburban or rural locations.

Direct Effects

It is difficult for an avid proponent of solar heating systems to admit, even to himself, that there are potential environmental problems of solar heating, cooling and process heat applications. Yet, the evidence is undeniable. People are willing to overlook shortcomings in a few, novel demonstrations of solar technology, but when such uses become commonplace the adverse impacts become evident. Some of the anticipated problems are:

- Contamination of groundwater by corrosion inhibitors, algaecides and antifreezes
- Glare from collectors
- Interference from adjacent structures
- Danger of falling glass.

The lack of large scale use of solar collectors prevents quantitative assessment of these effects, but some general observations are made.

Contamination of Ground Water: The one serious drawback to using water as a storage and heat transfer fluid is the problem of corrosion. The problem is certainly solvable but, based on current trends, can involve the use of chemical inhibitors that are potentially environmental problems. The best solution to the corrosion problem will likely be toxic compounds such as the chromate family of inhibitors. The inhibitor will get into the ground water from spillage during installation and checkout, and from periodic maintenance and corrosion.

Glare: Collectors that are tiltable such that they follow seasonal variations in elevation of the sun will likely not pose any glare problem to people on the ground. This is due to the fact that most of the reflected energy will go back into space rather than to the ground. Unfortunately, it is difficult to design a variable tilt collector into the roof of most house designs, so the majority of solar collectors will be fixed in one tilt position. The optimum tilt varies with latitude, weather conditions, and particularly with use patterns, but nominal tilt angles will be 30 to 60 deg from the horizontal. This will definitely cause glare on surrounding areas (particularly in summer) which can be very offensive.

Some ways to minimize this glare are:

- Use a transparent cover that has a matte finish, such as rolled glass,
- Install collectors, such that all the transparent covers are not in the same plane. This will break up the reflected sunlight.

Glare to vehicles in the air is not considered to be any more of a problem than glare from swimming pools, etc. The natural imperfections in flatness of the covers will break up the reflected light into a harmless glimmer for aircraft more than a few hundred feet high. If an aircraft is closer than that, the aircraft poses more threat to the solar collectors than the solar collectors do to the aircraft. A house near the end of an airport runway where large jet planes takeoff would be a good place to test the structural integrity of solar collectors. It is anticipated that sound from a jet airplane during takeoff would cause broken glass and leaks in a collector.

Interference by Adjacent Structures: Most people think that a solar collector needs a clear, unobstructed view of the southern sky in order to function properly. While such a view is desirable it is not necessarily required. It is possible for man to have his trees and solar heat, too. What is required is judicious placement of trees and an occasional pruning. Collector systems designed for heating and domestic hot water are not significantly affected by early morning and late afternoon shading. This is because very little energy is normally collected before about 9 o'clock and after about 3 o'clock (solar time). Shading the house during the morning and afternoon during the summer offers benefits in reduced air conditioning demands which may outweigh the winter benefits of no shading. Deciduous trees should minimize shading problems, because they shed their leaves in winter, when maximum heating loads occur.

So far, the discussion has been of the solar homeowner's own trees or toolshed shading his own collector. Problems are likely to arise when it is the neighbor's Lombardy populars that are doing the shading. Before, it was a question of asthetics, but suddenly it becomes a problem that has environmental, legal, and social implications. The environmental result may be a significant reduction in trees in residential areas.

Danger of Falling Glass: Most solar collector installations, particularly residential, will be on the roof (hopefully, most new construction will make the collectors a part of the roof structure). Until a better glazing material than glass is found, a large amount is going to be put up on rooftop solar collectors. Adequately stressed (such as with a big rock) any glass will break, even tempered glass. Gutters might catch most of the broken glass, but a lot of it is likely to fall off the roof. This could pose real hazards to anyone (but particularly small children) who happen to be in the yard.

Natural forces, such as hail and high winds, can also cause flying glass from collectors. Wind can pull large sheets of glass from their frames (for example, the John Hancock building) if the support is not properly designed and installed.

At least a few solar heating systems will eventually be installed by almost every builder of homes in the United States. There will be a learning period (and a fast buck, fly-by-night period) during which quality of construction will be questionable. Steps will have to be taken to prevent a serious problem of falling glass by legislating quality standards and inspection techniques.

On the positive side of solar energy, there are some environmental problems that should be enumerated that will not be present with flat plate solar collectors. Some of the more important ones are:

- Reduced fossil fuel consumption is the primary benefit to society. Included is a reduction in all of the adverse effects of coal mining and combustion and decreased dependence on natural gas and imported oil. The primary benefit to the user must be reduced cost to heat and/or cool his house.
- No air pollution as a direct result of solar collector use.
- Reduced heat imbalance. The solar collector causes less increase in the net solar energy remaining on earth in the form of heat than does an asphalt shingle roof, for instance.
- Few land use problems, since most houses have ample roof space for collectors.
- Few adverse visual effects since one criterion for a builder is to produce a home that will be acceptable to potential buyers. A well built collector is not an eyesore; it is a respectable, functional addition to a house.

Indirect Effects

Two major indirect effects of flat plate solar collector applications fall under two major headings:

- The change in raw material uses due to the formation of a new widespread product, and
- The effects of forming a new industry which reduces the market for an existing industry.

Raw Material Usage: As discussed previously, the actual materials to be used in large scale solar collector production is still to be determined. For purposes of this environmental assessment, however, an estimate was made from the best available information and is presented in Table 28. The data are shown as the amount of major materials used for the entire collector system. This includes plumbing, storage, heat exchangers and collector. Many such tabulations appear to have omitted peripheral hardware. Even though these use rates are significant, the impact on total production of these materials will not be significant.

TABLE 28. SOLAR HEATING AND COOLING MATERIALS REQUIREMENTS

Material	Cumulative Usage, 10^6 tons through year		
	1985	2000	2020
Aluminum	0.07	1.0	5.7
Steel	0.60	9.0	50.0
Copper	0.10	1.5	8.0
Glass	0.40	6.0	32.0

Industry Changes: The transportation costs for solar hardware, collectors in particular, would appear to stimulate regional manufacturing. The relatively simple construction of solar collectors has already attracted a multitude of small industries (sheet metal shops, for example) to develop and market a solar collector. However, most of these industries are still waiting for their first big collector order, and it is likely that a major portion of the nation's solar collectors will be furnished by, through or for big manufacturers. These big industries (such as PPG, Revere Copper, Dow Corning, etc.) will simply expand their product lines to include solar collectors, so the impact of solar hardware as a new industry will probably not be large.

The impact of solar hardware on existing industries such as conventional fuel heaters, will not be as great as might be expected. The nature of solar energy is such that backup systems will almost always be required for space heating and industrial process heating. Even solar air conditioning will have backup heating elements. However, due to the high initial cost of some types of conventional systems (such as heat pumps, coal or oil furnaces) they probably will not be used as backup, to solar systems. Instead, those of low initial cost systems, such as electrical resistance heaters, will likely be used. It is highly unlikely, for example, that a conventional vapor compression air conditioner will be used as a backup to a solar heat driven absorption type air conditioner. Instead, a backup heat source for the absorption unit will be used.

Recommended Research

The direction that solar hardware development is to take during the next decade is currently being shaped by government funding of R&D and demonstrations. The environmental implications of these studies are normally made a part of the study. However, some basic research needs to be conducted on three topics.

- The environmental impact of various corrosion inhibitors, algaecides, etc., should be investigated.

Consideration should be directed toward establishing the amounts of these chemicals that are expected to be discharged intentionally or unintentionally.

- The extent of the problem of glare from collectors should be assessed. Undoubtedly, glare can be annoying; but will it cause accidents or other such serious problems?
- Tests should be performed on vulnerability to damage and resulting human hazards from thrown objects, sonic boom, seismic events, etc.

Summary

Table 29 contains a concise summary of some of the points discussed in this chapter.

TABLE 29. FLAT PLATE COLLECTOR SYSTEMS SUMMARY

Environmental Effects		Millions of lbs/year		
		1985	2000	2020
Direct Effects				
• Corrosion Inhibitors		.2	3	16
• Heat Transfer Fluids		.3	4	25
2. Glare				
• Ground to Air (No Appreciable Effect)				
• Ground to Ground (Possible Large Effect for Residential Use)				
3. Reduced Consumption of Fossil Fuel (Equivalent Gallons of Oil)		60×10^6	830×10^6	$4{,}640 \times 10^6$
Indirect Effects				
1. Additional Cumulative Mineral Uses				
• Aluminum	(Millions of Tons)	.07	1.0	5.7
• Steel		.6	9.0	50
• Copper		.1	1.5	8.0
• Glass		.4	6.0	32

Suggestions

1. Put out list of EPA recommended collector fluids and inhibitors.
2. Study reaction of glare from collectors by simulating collectors in urban community.
3. Study vulnerability to hazards.

SECTION VII

REFERENCES

1. Energy Research and Development Administration. A National Plan for Energy Research, Development, and Demonstration: Creating Energy Choices for the Future Vol. 1: The Plan, ERDA-48, Washington, D.C., June 1975.
2. Energy Research and Development Administration. A National Plan for Energy Research, Development, and Demonstration: Creating Energy Choices for the Future, Vol. 2: Program Implementation. ERDA-48, Washington, D.C., June 1975.
3. Energy Research and Development Administration. National Program for Solar Heating and Cooling (Residential and Commercial Applications. ERDA-23A, Washington, D.C., October 1975.
4. Energy Research and Development Administration. Preliminary Definition Report — National Solar Energy Research, Development, and Demonstration Program. ERDA-49, Washington, D.C., June 1975.
5. Office of Technology Assessment. An Analysis of the ERDA Plan and Program. U.S. Congress, Washington, D.C., October 1975.
6. Prince, M.B. Photovoltaic Branch, Division of Solar Energy, ERDA, Private Communication, February 1976.
7. Dickson, E.M. Solar Energy. Control of Environmental Impacts from Advanced Energy Sources. EPA-600/2-74-002, Stanford Research Institute and USEPA, Washington, D.C., March 1974.
8. Griffith, L. A Position Paper on Solar Energy. Special Studies Staff, IERL, USEPA, Research Triangle Park, North Carolina, August 1975.
9. U.S. Atomic Energy Commission. Proposed Final Environmental Statement, Liquid Metal Fast Breeder Reactor Program, Vol. III, Alternative Technology Options. WASH-1535, Washington, D.C., December 1974.
10. Sholl, M. The MITRE Corporation, Bedford, Massachusetts, Private Communication, February 1976.
11. Wallach, M. Lawrence Berkeley Laboratory, Private Communication, February 1976.
12. Benson, J.W. Energy Research and Development Administration, Private Communication, February 1976.
13. Gilmore, D., Environmental Protection Agency, Las Vegas, Nevada, Private Communication, February 1976.

14. Zeren, R.W. Electric Power Research Institute, Private Communication, January 1976.

15. Anon. Environmental Effects of Solar Energy to be Probed. Chemical Engineering, Vol. 82, No. 27, 1975, p. 27.

16. Cherry, W.R. Agricultural and Process Heat Branch, Division of Solar Energy, ERDA, Private Communications, January and February 1976.

17. Wolf, M. Photovoltaic Power. Astronautics and Aeronautics, Vol. 13, No. 11, November 1975, p. 28.

18. Hickok, F. Handbook of Solar and Wind Energy. Cahners Publishing Co., Inc., Boston, Massachusetts, 1975.

19. Killian, H. J., G. L. Dugger, and J. Grey, eds: Solar Energy on Earth – An AIAA Assessment. American Institute of Aeronautics and Astronautics, New York, April 1975.

20. Greene, G.U. Cadmium Compounds. Kirk-Othmer Encyclopedia of Chemical Technology, 2nd Ed. Vol. 3, Interscience, New York, 1964, p. 899.

21. Doty, J.P., Eagle-Picher Company, Miami Oklahoma, Private Communication, February 1976.

22. Williams, J.R. Solar Energy Technology and Applications, Ann Arbor Science Publishers, Inc., Ann Arbor, Michigan, 1975.

23. National Science Foundation and Interagency Task Force for Solar Energy. Solar Energy Volume. Project Independence Blueprint Final Task Force Report, Federal Energy Administration, November 1974.

24. Science and Public Policy Program. Energy Alternatives: A Comparative Analysis, University of Oklahoma, Norman, and USGPO, Washington, D.C., May 1975.

25. Szego, G.C. The U.S. Energy Problem, Vol. 2, Appendices, Part B, NSF RANN 71-1-3, NTIS No. PB-207 519, Inter Technology Corp., Warrenton, Virginia, November 1971.

26. Szego, G.C. The U.S. Energy Problem, Vol. I: Summary. NSF-RANN 71-1-1, NTIS No. PB 207-517, InterTechnology Corporation, Warrenton, Va., November 1971.

27. Sears, D.R. An Environmental Assessment of a 500 MW Hydrogen Air Fuel Cell Peak Shaving Power Plant. LMSC-HREC TR D496563, Lockheed Missiles & Space Company, Huntsville, Alabama, 1975.

28. Parrish, W.R., R.O. Voth, J.G. Hust, T.M. Flynn, C.F. Sindt, and N.A. Olien. Selected Topics in Hydrogen Fuel. NBS Special Publication No. 419, National Bureau of Standards, Boulder, Colorado, May 1975.

29. Hausz, W., G. Leeth, D. Luechk, and C. Meyer. Hydrogen Systems for Electric Energy, TEMPO Report No. 72TMP-15, General Electric Company, Santa Barbara, California, April 1972.

30. Post, R.F., and S.F. Post. Flywheels. Scientific American, Vol. 229, No. 6, December 1973, p. 17.

31. Lawson, L.J., AiResearch Manufacturing Company of California, Division of Garrett Corporation, Torrence, California, Private Communication, Februrary 1976.

32. U.S. Atomic Energy Commission. Government-Wide Report to OMB on Energy Storage R&D Program Strategies and Implementation Plans. Division of Applied Technology, Washington, D.C., June 1974.

33. Fernandes, R.A. Hydrogen Cycle Peak-Shaving for Electric Utilities. Paper presented at the 9th Intersociety Energy, Conversion Engineering Conference, San Francisco, California, 1974

34. Williams, J.R. Geosynchronous Satellite Solar Power. Astronautics & Aeronautics, Vol. 13, No. 11, November 1975, p. 46.

35. Grosskreutz, J.C. Criteria and Procedures for Siting Central Solar (Thermal)/Electric Generating Stations. Preprint of paper presented at U.S. Sect. Meeting, International Solar Energy Society, Ft. Collins, Colo., August 1974 (Black & Veatch, Consulting Engineers, Kansas City, Missouri). See also: Site Selection Guide for Solar Thermal Electric Generating Plants, Special Report prepared for NASA-Lewis Research Center (Contract No. NAS3-18014) by Black & Veatch Consulting Engineers, Kansas City, Missouri) June 1974; Selecting Preferred Sites for a Solar Power Station Using Solar/Climatic Data, Special Report prepared for NASA-Lewis Research Center (Contract No. NAS3-18014) by Honeywell Systems & Research Center, 2600 Ridgeway Parkway, Minneapolis, Minnesota, October 1973; and On-Site Survey of Candidate Solar/Electric Power Plant Sites, Special Report prepared for NASA-Lewis Research Center (Contract No. NAS3-18014) by Honeywell, Inc./ Black & Veatch, June 1974. (Available through Honeywell Systems & Research Center, Minneapolis, Minnesota.

36. Auburn University Engineering Systems Design Summer Faculty Fellows. MEGASTAR: The Meaning of Energy Growth: An Assessment of Systems, Technologies, and Requirements. CR-120338, National Aeronautics and Space Administration, September 1974.

37. See for example: Federal Register, 40 FR 55334, 55343, November 28, 1975, cf. esp. Section 130.17, p. 55341.

38. See, for example: (a) Jones, K. Hydrology of Limestone Karst in Greenbrier County, West Virginia. Bulletin 36, West Virginia Geological and Economic Survey, Charleston, West Virginia, 1973; and (b) Bailey, L., and A.M. Malatino. Contamination of Ground Water in a Limestone Aquifier in the Stevenson Area. Alabama Circular 76, Geological Survey of Alabama, University, Alabama, 1971.

39. Thomas, H.E., Water. U.S. Dept. of Agriculture Yearbook. Government Printing Office, Washington, D.C., 1955, p. 66.

40. See for example: Kimball, T. Is There an Inherent Conflict Between Good Environmental Management and Energy Production? in Magnitude and Deployment of Energy Resources, ERDA, Oregon State Board of Higher Education, and Oregon State University, Corvallis, Oregon, September 1975, p. 209.

41. See for example: (a) Assessment of Environmental Impact of Alternate Sources for Electrical Energy. Oak Ridge National Laboratory, Oak Ridge, Tennessee, ORNL-5024, 1974; and (b) Robinson, N. Solar Machine. Procedures, World Symposium on Applied Solar Energy, Phoenix, Arizona, 1-5 November 1955.

42. Lodge, J.P., Jr., Chairman, Colorado Air Pollution Control Commission, and J. Pate, National Center for Atmospheric Research, Private Communications, April 1973.

43. Reese, K.M. Strong Electric Fields Spur Growth of Chicks. Chemical and Engineering News, 26 January 1976, p.40.

44. Anon. Power-Line Radiation Affects Earth's Magnetosphere. Physics Today, December 1975, p. 17.

45. Cermak, J.E. Air Motion In and Near Cities — Determination by Laboratory Simulation: CEP 70-71 JEC27, Fluid Mechanics Program, College of Engineering, Colorado State University, Ft. Collins, 1971.

46. Cormak, J.E., Director Fluid Mechanics Program, Department of Civil Engineering, Colorado State University, Ft. Collins, Private Communication, February 1976.

47. Auer, A. H., Natural Resources Research Institute, Laramie, Wyoming, Private Communication, February 1976.

48. Holden, C. Hail Suppression Up in the Air, Science, Vol. 191, No. 4230, March 1976, p. 932.

49. Atlas, D., National Center for Atmospheric Research, Boulder, Colorado, Private Communication, May 1973.

50. Decker, G.L., R.W. Barnes, R.E. Sampson, and V.L. Prentice. Evaluation of New Energy Sources for Process Heat. Dow Chemical Company, Midland, Michigan, and Environmental Research Institute of Michigan, September 1975.

51. Strickland, G., and J.J. Reilly. Operating Manual for the PSE&G Hydrogen Reservoir Containing Iron Titanium Hydride. BNL 50421, Brookhaven National Laboratory, February 1974.

52. Lueckel, W.J., and P.J. Farris. The FCG-1 Fuel Cell Power Plant for Utility Use. Presented at the Summer Meeting of the IEEE Power Engineering Society, 14-19 July 1974.

53. Manikowski, A. Lockheed Missiles & Space Company, Sunnyvale, California, August 1975.

54. Gregory, D.P. A Hydrogen-Energy System. American Gas Association, August 1972.

55. Dickson, E.M. Hydrogen as an Energy Carrier. Control of Environmental Impacts from Advanced Energy Sources. EPA-600/2-74-002, Stanford Research Institute and USEPA, Washington, D.C., March 1974.

56. Press Release No. 76-50, Marshall Space Flight Center, Huntsville, Alabama, 5 March 1975.

57. Stevens, Briscoe, Space Sciences Laboratory, Marshall Space Flight Center, Huntsville, Alabama, Private Communication, March 1976.

58. Sulyma, P.R., Lockheed Missiles & Space Company, Huntsville, Alabama, Private Communication, February 1976.

59. Mumford, W.H. Heat Stress Due to R.F. Radiation. Procedures IEEE, Vol. 57, 1969.

60. Michaelson, S.M., and C.H. Dodge. Soviet Views on the Biological Effects of Microwaves — An Analysis. Health Physics, Vol. 21, July 1971, p. 108.

61. Glaser, P. Power from the Sun Via Satellite. Testimony before the House Subcommittees on Space Science and Applications, and Science and Astronautics, 24 May 1973.

62. U.S. Bureau of Mines. Mineral Facts and Problems. Bulletin 650, 1970 Edition U.S. Bureau of Mines, Washington, D.C., 1970.

63. Wade, N. Raw Material: U.S. Grows More Vulnerable to Third World Cartels. Science, Vol. 183, 18 January 1974, p. 185.

64. Brobst, D.A., and W.P. Pratt (eds). United States Mineral Resources, USGS Professional Paper 820, Government Printing Office, Washington, D.C., 1973.

65. de la Breteque, P. Gallium. Kirk-Othmer Encyclopedia of Chemical Technology, Vol. 10, 2nd Ed., Wiley-Interscience, New York, 1966, p. 311.

66. Donnay, J.D.H., G. Donnay, E.G. Cox, O. Kennard, and M.V. King. Crystal Data, Determinative Tables, Second Edition. ACA Monograph No. 5, American Crystallographic Association, New York, 1963.

67. Hammond, A.L. Lithium: Will Short Supply Constrain Energy Technologies? Science, Vol. 191, 1976, p. 1037.

68. Anon. Report Estimates Energy Required to Produce Essential Primary Products. J. Air Pollution Control Association, Vol. 26, No. 2, 1976, p. 154.

69. Compilation of Air Pollutant Emission Factors, 2nd Edition. AP-42, USEPA, Research Triangle Park, North Carolina, 1973.

70. Fleisscher, M. et al. Environmental Impact of Cadmium: A Review by the Panel on Hazardous Trace Substances. Environmental Health Perspectives, No. 7, May 1974, p. 253.

71. Intersociety Committee. Methods of Air Sampling and Analysis. American Public Health Association, Washington, D.C., 1972.

72. Bond, R.G., C.P. Straub, and R. Prober. Handbook of Environmental Control, Vol. 1, Air Pollution, CRC Press, Cleveland, Ohio, 1972.

73. Natusch, D.F.S., J.R. Wallace, and C.A. Evans. Toxic Trace Elements: Preferential Concentration in Respirable Particles. Science, Vol. 183, January 1974, p. 202.

74. Hwang, J.Y. Trace Metals in Atmospheric Particulates and Atomic Absorption Spectroscopy. Analytical Chemistry, Vol. 44, No. 14, December 1972, p. 20A.

75. Lisk, D.J. Recent Developments in the Analysis of Toxic Elements. Science, Vol. 184, June 1974, p. 1137.

76. Taras, M., A.E. Greenberg, R.D. Hoak and M.C. Rand, eds. Standard Methods for the Examination of Water and Waste Water, 13th Edition, American Public Health Association, Washington, D.C., 1971.

77. Sterba, J.P. Reclamation Plan for Strip-Mined Land Stirs Debate. New York Times, 3 July 1974, p. 41.

78. Moody's Public Utility Manual, 1974, Moody's Investors Service, Inc., New York, 1974.

79. Bryant, A.H., III. Industrial Study and Appraisal: The Electric Utilities. Reynolds Securities, February 1976.

80. Nielsen, G.F. Coal Mine Development Survey Shows 492.6 Million Tons of New Capacity by 1985. Coal Age, Vol. 81, No. 2, February 1976.

81. Dials, G.E., and E.C. Moore. The Cost of Coal. Environment. Vol. 16, No. 7, September 1974, p. 18.

82. Hall, M., Poison Control Center, Atlanta, Georgia. Private Communication, February 1976.

83. Gruntfest, I. EPA Office of Toxic Substances, Washington, D.C., Private Communication, February 1976.

84. Crable, J.V., and D.G. Taylor. NIOSH Manual of Analytical Methods, HEW Publication No. (NIOSH) 75-121, Cincinnati, Ohio, 1974.

85. Eller, P. National Institute of Occupational Safety and Health, Cincinnati, Private Communication, February 1976.

86. Sax, N.I. Dangerous Properties of Industrial Materials, 4th Edition. Van Nostrand, New York, 1975.

87. International Labour Office Encyclopaedia of Occupational Health and Safety, McGraw-Hill and the International Labor Office, New York and Brno, Czechoslovakia, 1974.

88. Christensen, H.E., T.T. Luginbyhl, and B.S. Carroll. The Toxic Substances List 1974 Edition. National Institute for Occupational Safety and Health, Rockville, Maryland, 1974.

89. Fairhall, L.T., and F. Hyslop. The Toxicology of Antimony. Supplement No. 195 to the Public Health Reports, U.S. Public Health Service, Washington, D.C., 1947.

90. Gervais, R.L., and P.B. Bas. Solar Thermal Electric Power. Astronautics and Aeronautics, Vol. 13, No. 11, November 1975, p. 38.

91. a. Telkes, M. Thermal Energy Storage. Record of the Tenth Intersociety Energy Conversion Engineering Conference, Newark, Delaware, August 1975.

91. b. Telkes, M. Storage of Solar Heating/Cooling. ASHRAE Transactions, Vol. 80, Pt. II, 1974.

92. Hale, D.V., M.J. Hoover, and M.J. O'Neill. Phase Change Materials Handbook. NASA CR-61363, Lockheed Missiles & Space Company, Huntsville, Alabama, September 1971.

93. General Electric Corporation. Solar Heating and Cooling of Buildings – Phase O, Final Report. Vol. 2, NSF-RA-N-74-021B, May 1974.

94. Steadman, P. Energy, Environment and Building, Cambridge University Press, Cambridge, England, 1975.

95. TRW Corporation. Solar Heating and Cooling of Buildings – Phase O, Final Report. Vol. 2, NSF-RA-N-74-022B, May 1974.

96. Westinghouse Electric Corporation. Solar Heating and Cooling of Buildings – Phase O, Final Report. Vol. 2, NSF-RA-N-74-023B, May 1974.

97. Energy Research and Development Administration. Catalog on Solar Energy Heating and Cooling Products, ERDA-75, ERDA Technical Information Center, Oak Ridge, Tennessee, October 1975.

98. Science Policy Research Division, Congressional Research Service, Library of Congress. Survey of Solar Energy Products and Services – May 1975. Committee on Science and Technology, 94th Congress, June 1975.

99. Moore, S.W., J.D. Balcomb, and J.C. Hedstom. Design and Testing of a Structurally Integrated Steel Solar Collector Unit Based on Expanded Metal Plates. Los Alamos Scientific Laboratory report presented at the U.S. Section Meeting of the International Solar Energy Society, Ft. Collins; Colorado, 20-23 August 1974.

100. Proceedings of the Workshop on Solar Energy Storage Subsystems for the Heating and Cooling of Buildings, Charlottesville, Va., April 1975.

APPENDIX A

ENERGY FORECAST BACKGROUND INFORMATION

The energy scenario analysis introduced in Section III contained very little descriptive background information on these energy forecasts. The assumptions and definitions of these five energy forecasts are presented in detail in the following sections. The information presented is extracted from Ref. 1.

SUPPLY AND DEMAND ASSUMPTIONS – SCENARIO 0 – NO NEW INITIATIVES

Supply

- Oil and gas production draws on remaining recoverable resources: (1) according to lower estimates by the U.S. Geological Survey (1975) and the National Academy of Sciences (Ref. 1, p. IV-2), and (2) without tertiary or other new recovery.
- Coal and nuclear converter reactors continue to expand to meet electricity demand, limited by ability to construct or convert plants.
- Other energy sources (e.g., geothermal, hydroelectric, and urban wastes) expand according to historic projections of existing technologies which do not reflect recognition of a serious energy problem.

Demand

- Current consumption patterns continue with no improvement in residential, commercial, or industrial end-use and most transportation efficiencies
- A 40% efficiency improvement for energy use in automobiles is realized by 1980 because of a trend toward smaller autos.

SCENARIO I – IMPROVED EFFICIENCIES IN END-USE

Supply*

- Domestic oil and gas production is increased above the base case (Scenario 0) by new enhanced recovery technologies.

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*Other assumptions are essentially those of Scenario 0.

- Solar heating and cooling are introduced.
- Geothermal heat is used for process and space heating.
- Waste materials are employed as fuels or are recycled to save net energy in production.

Demand*

- Residential and commercial sector technologies are improved with regard to:
  - The structure itself in order to reduce heating and cooling requirements
  - Improved air conditioners, furnaces, and heat pumps
  - Appliances and consumer products.
- Industrial process efficiency improvements are achieved in:
  - Process heat and electric equipment
  - Petrochemicals
  - Primary metals.
- Efficiencies of electricity transmission and distribution are increased.
- Improved transportation efficiencies derived from new technologies (in contrast to efficiencies from smaller vehicles) are assumed for land and air transportation.
- Waste heat (e.g., from electric generation) is employed for other low-grade uses now requiring separate energy input.

SCENARIO II – SYNTHETIC FUELS FROM COAL AND SHALE

Supply**

- Substantial new synthetic fuels production is introduced from:
  - Coal
  - Oil Shale
  - Biomass

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*Other assumptions are essentially those of Scenario 0.

**The assumptions, unless otherwise stated, are those of the previous scenarios to ensure that comparisons are being made only of the impacts of stated energy options.

- Enhanced oil and gas recovery levels of Scenario I are included
- Under-used solar, geothermal, and waste sources included in Scenario 0 are not included here.

Demand*

- No end-use efficiency improvements are assumed.

SCENARIO III – INTENSIVE ELECTRIFICATION

Supply**

- Electric power is intensively generated by coal and nuclear power as in prior scenarios
- New technology energy sources are introduced as available to generate electricity
  - Breeder reactors
  - Solar electric (wind, thermal, photovoltaics and ocean thermal)
  - Fusion
  - A minimal contribution is assumed from waste materials (as in Scenario 0).

Demand**

- Improved electric conversion efficiences are introduced
- Widespread use of electric autos begins
- Technologies to improve efficiency of electricity transmission and distribution are implemented

SCENARIO IV – LIMIT ON NUCLEAR POWER

Supply

- Converter reactor energy levels are constrained to 200,000 megawatts electric
- Coal electric is at the levels in other scenarios to permit coal to be employed for synthetics

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*The assumptions, unless otherwise stated, are those of the previous scenarios to ensure that comparisons are being made only of the impacts of stated energy options.

**Supply assumptions are consistent with Scenario I and demand assumptions with Scenario 0, unless otherwise stated.

- Additional sources of electricity depend on
  - Accelerated geothermal development (more than a factor of two over Scenario III)
  - Accelerated solar development (a factor of two over Scenario III)
  - Fusion as in Scenario III
- Solar and geothermal heating are used (as in Scenarios I and III)
- Synthetic fuels are produced from coal, shale, and biomass at the level of Scenario II.

Demand

- Industrial efficiency aspect of conservation scenario (Scenario I) is included
- Electric transmission efficiencies are not included, as electricity use grows too slowly to justify changes.

SCENARIO V – COMBINATION OF ALL NEW TECHNOLOGIES

Scenario V analyzes a case in which a combination of all major energy packages, including nuclear, are simultaneously commercialized (i.e., improved end-use, synthetic fuels, and electrification). The specific inputs for this scenario are those previously summarized. It should be noted, however, that the inputs are not simply additive; rather, potential energy supplies are drawn on only as necessary to meet projected demand.

The senario results highlight the unbalanced impact of the total use of technologies in meeting energy needs:

- A surplus of options for producing electricity is likely to exist (e.g., neither coal nor nuclear options are hard pressed to meet demand in Scenario V).
- Ability to meet liquid and gas requirements remains marginal even if all current technological options are vigorously pursued.
- Many technologies can complete to meet end-use needs in some markets (e.g., utilities, industrial processes, and space heating); few can compete in others (e.g., transportation and petrochemicals).

INPUTS FOR SCENARIOS

Quantitative energy supply and demand data which result from the preceding assumptions are summarized in the Table A-1.

TABLE A-1. INPUTS FOR SCENARIOS (REF. 1)

Item	Quantities	
	Year 1985	Year 2000
Scenario 0 — No New Initiative		
Electric Supply (GW_e):		
Coal	295	
Nuclear — moderate growth no LMFBR	185	720
Hydroelectric — moderate growth	86	92
Geothermal — expansion of geysers	5	10
Oil and gas	Remainder of demand*	
Direct Fuels Production:		
Oil (MBD)	10.1	5.3
Gas (TCF)	21.5	15.4
Coal	As needed	
Urban waste (Quads)	0.1	0.1
Consumption Technologies:		
Automobile Efficiency (MPG)	17.5	20.0
Scenario I — Improved Efficiencies in End Use		
Electric Supply	Same limits as in Scenario 0*	
Direct Fuel Supply:		
Oil (amount added for tertiary recovery) (MBD)	1.5	3.6
Gas (amount added for enhanced recovery (TCF)	5.0	7.4
Solar heating and cooling (Quads)	0.25	3.5
Geothermal heat (Quads)	0.2	1.0
Waste material use (including recycling) (Quads)	2.0	7.5
Waste Heat Use for Heat and Power	0.4	3.0

*Amounts used less in some cases.

TABLE A-1. (CONTINUED)

Item	Quantities Year 1985	Year 2000
Consumption (% improvement):	Scenario I — (Continued)	
Buildings:		
— Shell	10	15
— Heating and cooling equipment	10	20
— Other appliances and consumer products	10	25
Industry:		
— Process heat and electrical equipment	10	12
— Petrochemicals	5	25
— Primary metals	10	20
Electric power transmission and distribution	—	25
Transportation		
— Land transport other than autos	10	20
— Aircraft	15	15
— Autos (fleet average)	18.7	28
Scenario II — Synthetics from Coal and Shale		
Electric Supply	Same as Scenario 0	
Direct Fuels Supply		
Oil and gas	Same as Scenario I	
Synthetic crude and pipeline quality gas from coal (or equivalent barrels of oil)	0.7	7.0
Oil from shale (above ground and in situ)	0.5	4.0
Biomass conversion (oil equivalent)	0.025	0.75
Solar and geothermal heat	None	
Urban wastes:	Same as in Scenario I	

TABLE A-1. (CONTINUED)

Item	Quantities: Year 1985	Year 2000
Scenario II – (Continued)		
Waste Heat Use and Electric Transmission and Distribution	Same as in Scenario I	
Consumption	Same as in Scenario 0*	
Scenario III – Intensive Electrification		
Electric Supply (GW_e):		
Coal electric (max. in 1985)	295	not limited
Hydroelectric	86	92
Nuclear converter reactors	225	720
Breeder reactors	0	80
Solar elec. power	1	50
Fusion power	0	1
Geothermal elec. power	10	40
Oil and gas electric power		
Direct Fuels:	Same as in Scenario I**	
Consumption:		
Same as Scenario II except electric autos	1	10
Scenario IV – Limited Nuclear Power		
Electric Supply:		
Coal electric (max. level in 1985)	295	not limited
Hydroelectric power (same)	86	92
Nuclear converter reactors	185	200
Solar electric power	5	100
Fusion power	0	1
Geothermal	20	100
Oil and gas	Balance of demand	

* For all end-use efficiencies.

**Except waste materials and recycling added at base level.

TABLE A-1. (CONCLUDED)

Item	Quantities	
	Year 1985	Year 2000
Scenario IV – (Continued)		
Direct Fuels Supply:		
Same as Scenario II (Synthetic Fuels), plus:		
– Solar Heating and cooling	0.25	3.5
– Geothermal heat	0.20	1.0
Consumption:		
Same as Scenario 0, the following efficiency improvements from Scenario I:		
– Process heat and electric equipment	10	12
– Petrochemicals	5	25
– Primary metals	10	20

APPENDIX B
CONVERSION FACTORS

1 acre	= 4.047×10^3 square meters
1 Btu	= 2.928×10^{-4} kilowatt-hours
1 foot	= 3.048×10^{-1} meters
1 inch	= 2.54×10^{-2} meters
1 mile	= 1.609×10^3 meters
1 pound	= 0.4536 kilograms
1 quad	= 10^{15} Btu
	= 180 million barrels of petrolem*
	= 42 million tons of bituminous coal*
	= 0.98 trillion cubic feet of natural gas*
	= 293 billion kilowatt hours of electricity
1 sq. mi.	= 2.59×10^6 square meters
1 ton	= $9.072\ 10^2$ kilograms
1 Torr	= 1 millimeter Hg

*These values vary with the quality of fuel actually extracted and represent an average of recent production.

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

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15. SUPPLEMENTARY NOTES

16. ABSTRACT

Central station solar-electric plants and flat plate space heating installations are environmentally superior to their respective conventional alternatives because they produce little or no air and water pollution. Both kinds of installations will require storage systems, also relatively clean environmentally.

Land area required for central station solar plants will be large, but it is not as destructive or irreversible as with coal stripping. The ecological impact of solar plants can be serious as a result of vegetation destruction. Visual effects can be extensive, with no mitigating technology. Weather modifications may occur. Geosynchronous satellite generating stations could be environmentally catastrophic from pollution caused by large numbers of space tugs.

Some photovoltaic materials, such as gallium and cadmium may be resource limited. Indirect effects, resulting from the production of large quantities of photovoltaic materials, could be environmentally harmful.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Solar power generation Solar energy concentrators Solar heating Environmental engineering Pollution Land use	environmental assessment	10A 10B 13B 13H

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